Benchmarking analysis of digital light processing resins in terms of dimensional accuracy and geometric tolerances

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Benchmarking analysis of direct light processing resins in terms of dimensional accuracy and geometric tolerances

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Abstract

Additive Manufacturing (AM) is an innovative technology that is revolutionizing traditional manufacturing processes. Generally, following a *layer-by-layer* approach, in AM the final shape of the product is built through the progressive deposition of one or more materials. The most common extrusion-based AM technique for thermoplastic polymers is Fused Filament Fabrication (FFF), whilst for photopolymer resins, Direct Light Processing (DLP) and Stereolithography (SLA) are widely used. In the last years, DLP has spread rapidly, due to its low average cost and simple use. Moreover, a lower layer thickness can be used in DLP if compared to the FFF process. Therefore, hobbyists or amateur end users and many companies use DLP to achieve high dimensional accuracy and smooth surfaces for small products.

This work aims to evaluate the performance of three different DLP resins in terms of dimensional and geometrical accuracy. A benchmarking activity is carried out using a Rover printer by Sharebot to produce replicas of a reference part using Sharebot resins. After production, the dimensional inspection of the replicas was carried out using a Coordinate Measuring Machine (CMM) for comparison of the geometric features according to ISO IT grades and tolerances of the GD&T system. The results of this study are also compared with previous works from the literature in the conclusions.

Keywords: 3D Printing; DLP; benchmarking; dimensional accuracy; IT grades; GD&T.

1. Introduction

3D Printing is the term that is commonly used to refer to Additive Manufacturing (AM) techniques. It addresses a group of technologies that originated from the development of Rapid Prototyping (RP) [1]. These techniques allow designers, engineers and adopters to give shape to their ideas, starting directly from the CAD model of an object to produce a physical replica of it by a *layer-by-layer* approach for material addition [2]. Among the main advantages of 3D printing, design freedom and high customization are worth mentioning. Moreover, AM enables the fabrication of complex and unconventional shapes and integrated assemblies made of polymers, metals or ceramics.

Polymers and photopolymers are the most used materials in AM with a much wider variety than metals or ceramics. The Direct Light Processing (DLP) technique was invented after the Stereolithography (SLA) process. Unlike the latter uses a digital projector to cure the photopolymer resin under exposure to a UV light. The build platform is initially immersed into the vat containing the liquid resin. The cross-sectional geometry of the object to be fabricated is projected by the illuminated pixel of the UV projector at the bottom of the vat. In the regions where the resin is locally exposed to UV radiation for a certain time, the liquid polymer starts curing and solidifies. Thus the current layer of the object is created and the build platform raises from the vat by a distance that is equal to the thickness of

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the next part layer. The exposure process is then adapted to the next cross section to create the new layer (Fig. 1a) and the cycle repeats until the production of the part is complete [3].

As regards the dimensional accuracy and quality of DLP products, part deformation during the additive process is mainly influenced by the UV light intensity, the exposure time and the layer thickness as well as by the chemical composition of the resin. Moreover, resin polymerization leads to higher temperatures and, as a consequence, thermal gradients induce stresses and shrinkage [4].

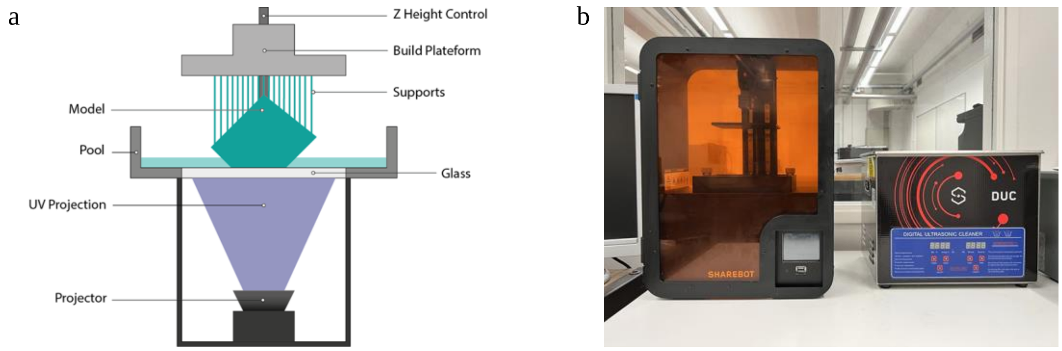


Fig. 1. DLP system scheme (a); Rover printer by Sharebot and ultrasonic cleaner (b).

When printing aesthetical parts, the absence of surface defects and high quality of surfaces with a good definition of details. Conversely, when technical or medical parts have to be fabricated, the dimensional accuracy and manufacturing tolerances are of paramount importance [5].

This work aims to investigate the dimensional and geometrical accuracy of 3d printed parts that is achievable with three different resins using a specific DLP printer, which is Rover by Sharebot (Fig. 1b). The study is carried out using a benchmarking approach that considers the printed replicas of a reference artifact [6, 7, 8, 9]. A specific artifact has been recently proposed by the authors with focus on photopolymers [10]. After printing, the replicas of the reference part were measured using a coordinate measuring machine (CMM). Subsequently, the measurement results are analysed to express the dimensional quality of the replicas using ISO standard IT grades [11, 12], while geometrical tolerances are considered according to the GD&T system [13].

The next section of the paper presents the geometry of the reference part and describes the experimental methods mode in detail. The third section focuses on the analysis of the dimensional measurements of the artifact replicas together with an evaluation and comparison of costs. Final considerations are included in the conclusions at the end.

2. Materials and methods

The methodology described in the following has been adopted by the authors for several years as a benchmarking procedure to assess the dimensional accuracy of many AM processes, for specific machines and materials. The replication of measurements and analyses allows for the thorough comparison of the results presented in several papers. However, with a focus on photopolymers, this work differentiates from the previous one [10] because the CMM measurements have been automated and a higher number of geometric features is included in the data analysis.

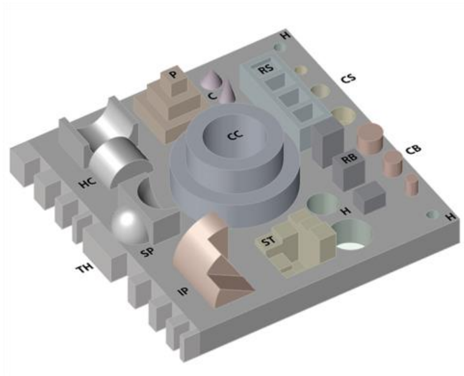
Moreover, this study considers just one specific DLP printer, which is the Rover machine by Sharebot, a 3d printer manufacturing company based in Nibionno (LC), Italy. The replicas of the reference artifact are printed using three different resins supplied by Sharebot. Therefore, differences in the printing accuracy of the machine mainly depend on the chemical composition of the resins and their properties. This investigation determines the range of dimensional accuracy achievable by Sharebot Rover depending on the DLP resin chosen for part production.

2.1. Reference part for benchmarking

The reference part for benchmarking of different 3d printing processes for photopolymers was designed including various geometries like cylinders, cones, spheres and prisms (Fig. 2a). The dimensions of these geometric features were defined to fit different ranges of the ISO basic sizes and their location was arranged to facilitate the inspection using one configuration of the CMM contact probe (Fig. 2b). More information about the reference artifact was given in the previous work by Minetola [10]. However, a short summary is provided hereafter for the sake of completeness.

The nominal dimensions of the reference part are 50 x 50 x 15 mm and the largest feature size is 20 mm. Thus, the sizes and distances, that can be evaluated using the artifact features, fit the first six ranges of the ISO basic sizes, as explained in the next section. The artifact has thirteen groups of small and medium features with simple shapes, as summarized in Table 1.

a



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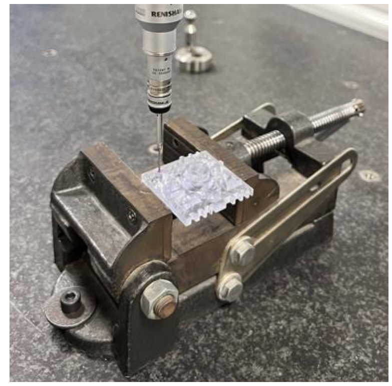

Fig. 2. Isometric view of the reference part with Feature IDs (a); part clamping and inspection with a touch probe (b).

Table 1. Feature description of reference part for benchmarking.

Feature group	Feature Type	Number of features	Feature Description
C	Cones	2	Base 5 mm – Height 8 mm – Angle 30° Base 3 mm – Height 10 mm – Angle 30°
CB	Circular bosses	3	Diameter 2, 3, 4 mm – Height 3 mm
CC	Coaxial Cylinders	2	Diameter 15, 20 mm – Height 5 mm
CS	Circular Slots	3	Diameter 2, 3, 4 mm – Depth 3 mm
H	Holes	6	Diameter 2, 3, 5, 7, 10 mm
HC	Horizontal Cylinders	2	Diameter 8 mm – Length 6 mm
IP	Inclined Planes	3	Angle 30°, 60°, 90°
P	Pyramid (Square boxes)	3	Square base 3x3, 5x5, 7x7 mm – Step height 3 mm
RB	Rectangular Bosses	3	Base 3x4 mm – Height 3, 5, 7 mm
RS	Rectangular Slots	4	Base 3x4 mm – Depth 1, 3, 5, 7 mm
SP	Spheres	2	Concave or convex shape – Diameter 8 mm
ST	Staircase	9	Total height 9 mm (4 mm down; 5 mm up) Step of 1 mm
TH	Teeth	8	Representative of thin walls Master – From 4 mm to 1 mm Slave – From 5 mm to 2 mm

There are in total fifty geometric features (horizontal and vertical planes, classic geometries with simple surfaces) on the reference part. These are measured on the physical 3d printed replicas and measures are used for evaluating the dimensional accuracy and geometrical tolerances of the investigated DLP process.

2.2. Replica fabrication by DLP

The fabrication of the artifact replicas was carried out using the Rover printer of the Integrated Additive Manufacturing Centre (IAM@PoliTO) of the Politecnico di Torino. Rover is a small DLP printer built with the standard architecture of DLP systems. The digital projector is at the bottom of the machine and irradiates UV light at the frequency of 405 nm. Over the projector screen, the vat for loading the liquid photopolymer comes with a transparent FEP (Fluorinated Ethylene Propylene) membrane. The build platform on the top of the vat moves in the vertical direction with a high resolution of the Z-axis and raises from the vat at each new layer during the DLP printing operation. Rover main technical characteristics are listed in Table 2.

Table 2. Technical specifications of Sharebot Rover.

Characteristic	Value
Machine dimensions	460 x 353 x 200 mm
Weight	15 kg
Printing volume	62 x 115 x 100 mm^3
XY Resolution	47 μm
Z Resolution	20 - 100 μm

Rover can operate with a wide range of photosensitive resins, suitable for different technical applications. For the benchmarking activity, three different photopolymers supplied by Sharebot were used for the production of the artifact replicas. The three resins are named S-Clear, G-Strong and S-Hard. Except for the S-Clear that is transparent, they present a neutral grey color and ensure optimal performances, both visual and mechanical. The main mechanical properties of the resins are reported in Table 3.

Table 3. Main mechanical properties of Sharebot resins.

Characteristic	S-Clear	G-Strong	S-Hard
Elastic Modulus (E)	2310 MPa	1750 MPa	2560 MPa
Ultimate tensile strength (UTS)	47.3 MPa	30 MPa	49 MPa
Elongation at break	4.6%	4%	3.8%

In the AM workflow, some preliminary steps are necessary before part printing. These include the selection of part orientation, the generation of support structures for overhangs and the choice of process parameters. These steps were done using Pyramis slicer by Sharebot.

a b c d e f

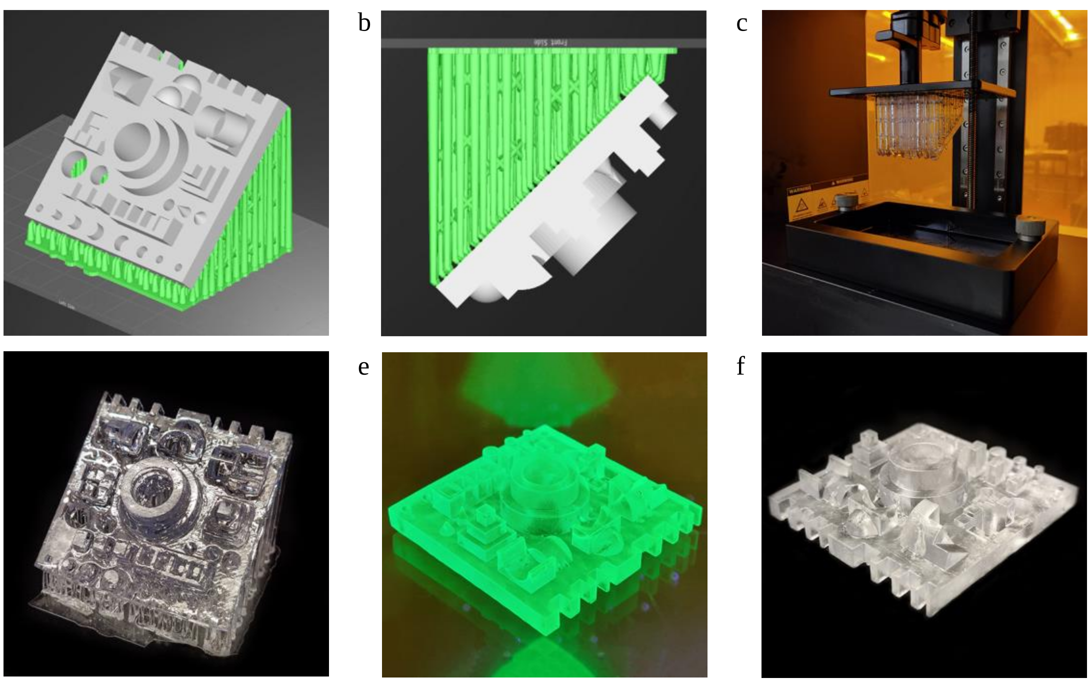

Fig. 3. Part with supports (a); build orientation (b); end of the print job for the S-Clear replica (c); as-built S-clear replica before post-processing (d); UV post-curing (e); finished part for inspection (f).

To reduce the contact area between each solidified layer and the FEP membrane at the bottom of the vat, the square base of the reference part was tilted 45° to the horizontal direction (Fig. 3a). This angle ensures that no support structure is needed for printing the geometric features of the artifact because each new layer is supported by the previous one. However, to connect the base of the artifact to the build platform, pillar supports were introduced in the bottom face of the square base (Fig. 3b). The chosen tilting angle also limited the extension of the projected area of supports on the platform. A smaller projected area reduces the risk of higher adhesion between the first thin printed layer of the photopolymer and the FEP. In the case of strong adhesion forces, the thin layers might detach from the build platform leading the DLP printing operation to fail.

The three replicas of the reference part were printed with a layer thickness of 100 μm and the 3d printing time was dependent on the sensitivity and reactivity of each resin to the UV radiation. Therefore, using Sharebot standard parameters (Table 4) a different exposure time was set for the three resins and the estimated print time was 9 hours and 28 minutes for the S-Clear replica (Fig. 3c), 6 hours and 10 minutes for the G-Strong replica, and 5 hours and 52 minutes for the S-Hard replica.

Table 4: Standard Sharebot parameters for the three different resins.

Resin	Exposure time of the first 5 bottom layers	Exposure time of the general layers	Scale factor in X / Y / Z
S-Clear	200000 ms	70000 ms	1 / 1 / 1
S-Hard	400000 ms	25000 ms	1 / 1 / 1
G-Strong	180000 ms	40000 ms	1.00204 / 1.00204 / 1

After DLP printing and separation from the build platform, all replicas needed post-processing treatments such as ultrasonic cleaning in isopropyl alcohol (IPA) to remove uncured liquid resin from cavities (Fig. 3d), manual removal of supports and post-UV curing. The post-curing process completes the polymerization process, which is initiated by the UV exposure during DLP printing. The post-curing treatment is carried out for 20 minutes using an oven with UV lamps for 120 W (Fig. 3e). After this treatment, the photopolymer is consolidated and less reactive so the replicas can be easily handled and used (Fig. 3f).

The 3d printed replicas of the reference part are shown in Fig. 4a, Fig. 4b and Fig. 4c for the G-strong resin, the S-Hard resin and the G-clear resin respectively. To better appraise the superficial finishing, a magnified view is also included in Fig. 4 for the bottom right area comprising the spheres (SP), the horizontal cylinders (HC) and some teeth (TH) of each replica.

a b c

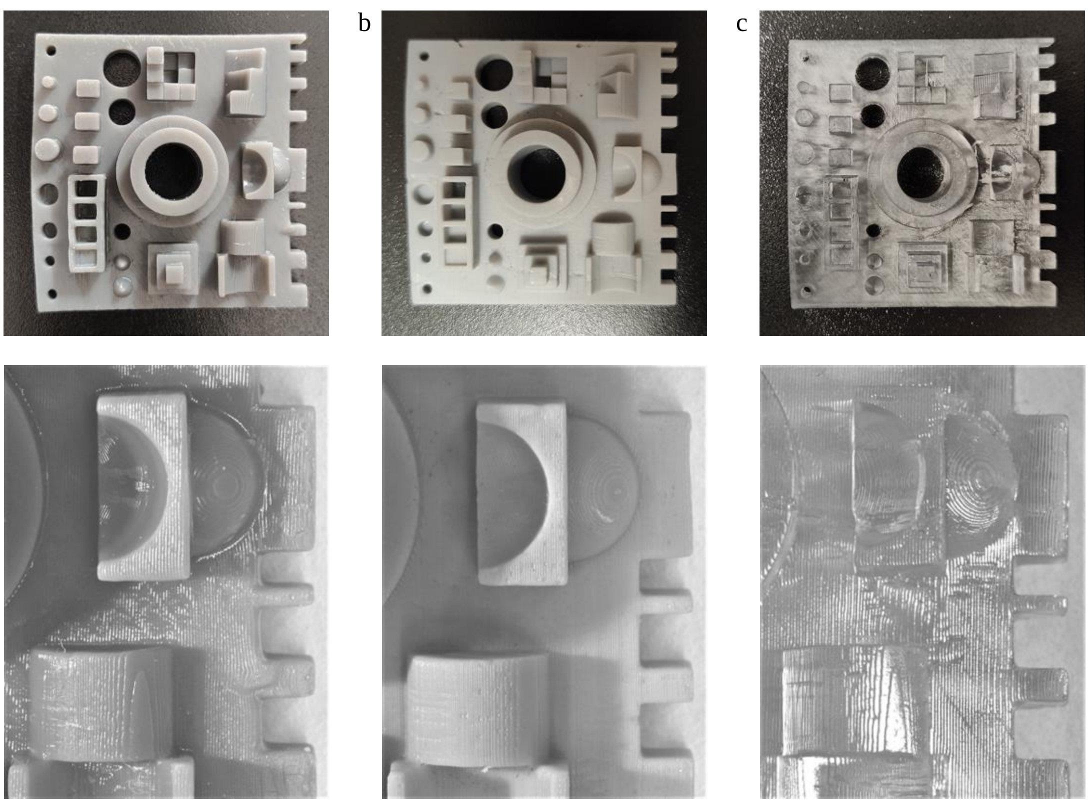

Fig. 4: Replica details – G-Strong (a); S-Hard (b); S-Clear (c).

All three parts had a deformed curved side on the left of the square base, close to the circular bosses (CB) or slots (CS) in Fig. 4. The deformed edge and side correspond to the bottom side surface of the artifact in the printing orientation of Fig. 3a. This surface was the first to be printed during the DLP process and it was probably subjected to higher stresses and deformations because of the earlier solidification of the resin.

The addition of support structures (Fig. 3b) connected to that side was not effective in constraining material deformation to preserve the ideal shape.

2.3. Dimensional inspection of the replicas

Every manufacturing process is influenced by several factors, such as material defects and deformations, environmental conditions, machine and tools wear. These elements affect the natural variability of the process and inevitably introduce deviations to the ideal conditions. For this reason, the dimensions of a real product differ from the ones of the nominal CAD model and the deviation is assumed as the dimensional accuracy of the process.

To determine the dimensional accuracy of a part and its related manufacturing process, ISO IT grades [11, 12] can be used. Therefore in this work, the benchmarking activity is carried out by measuring all geometric features of the reference artifact and by comparing the IT grades of the three different replicas made of Sharebot resins.

The dimensional inspection and measurements were completed using a coordinate measuring machine (CMM) model GLOBAL Image 07.07.07 by Brown and Sharpe Company, which is today part of the Hexagon Metrology group. According to ISO-10360/2 [14], this CMM has a nominal volumetric length measuring uncertainty MPE (Maximum Permissible Error) of 1.5 + L ⁄ 333 µm, where L is the measured length.

The evaluation of ISO IT grades requires the determination of the standard tolerance factor *i* through the formulas in Eq.1 and Eq.2, where *D* represents the geometric average of the nominal range of ISO basic sizes (Table 5). Due to the overall dimensions of the reference artifact, the maximum size associated with the geometric features of the replicas is included in the 30-50 mm range of ISO basic sizes, limiting the *i* factor to a maximum of 1.561 µm.

$$i = 0.45 \cdot \sqrt[3]{D} + D \cdot 10^{-3} \tag{1}$$

$$D = \sqrt{D_1 \cdot D_2} \tag{2}$$

Table 5: ISO basic sizes and respective standard tolerance factor *i*.

Nominal range	D_1 (mm)	1	3	6	10	18	30	50	80
	D_2 (mm)	3	6	10	18	30	50	80	120
Standard tolerance factor	*i* (µm)	0.542	0.733	0.898	1.083	1.307	1.561	1.856	2.173

Table 6: IT grades classification for 1-500 mm basic sizes - ISO 286-1:2010.

IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
7*i*	10*i*	16*i*	25*i*	40*i*	64*i*	100*i*	160*i*	250*i*	400*i*	640*i*	1000*i*	1600*i*	2500*i*

ISO IT grades are classified according to the value of the standard tolerance factor *i* as reported in Table 6. To determine the IT grade, the number *n* of tolerance units should be first computed. *n* represents the number of times that the standard tolerance factor *i* fits into the deviation of the generic measure D_{jm} from the nominal value D_{jn}.

The number *n* of tolerance units can be computed using Eq. 3, wherein D_{jn} represents the nominal dimension and D_{jm} is the measured one.

$$n_j = \frac{1000 \cdot |D_{jn} - D_{jm}|}{i} \tag{3}$$

An example of the determination of the *i* factor is summarized in Table 7. In this example, the *i* factor fits 136 times (*n* value) in the measured deviation, so the corresponding IT grade will be IT12 (Table 6).

Table 7: Example of determination of ISO IT grade.

Feature	Value
Nominal and measured dimensions	D_{jn} = 5 mm; D_{jm} = 5.1 mm
Corresponding nominal size range	(D_1, D_2) = (3, 6) mm
Standard tolerance factor	i = 0.733 μm
n factor	n_j = 136

For each measured feature of the reference artifact, the n_j value was computed for each replica and attributed to the corresponding range of ISO basic sizes. For each ISO range, the accuracy of the replica is then determined through IT grades by considering the 95th percentile of n distribution [15, 16, 17]. This specific value or threshold is assumed as the maximum dimensional error of the DLP machine for the combination of material and 3d printing parameters that were used for the fabrication of the replica.

In addition to the IT grades, geometrical tolerances of the replica features were expressed through the GD&T system, as reported in the next section about the experimental results of this study.

3. Experimental results

Considering the dimensions and the relative distances of the artifact features, the results of the benchmarking activity involved the analysis of over 1800 measured deviations for every replica. These deviations were computed from the measures collected using the CMM for the inspection of 125 features for each part.

To provide more robust results, the measurements were replicated three times for each part and the arithmetical mean of each measure was then considered in the analysis of inspection results. As regards geometric tolerances, the GD&T values computed by the inspection software PC-DMIS (version 2020 R1 by Hexagon Metrology) of the CMM were collected and classified into different categories: coaxiality, cylindricity, flatness, parallelism, perpendicularity, and etc. depending on the type of geometric entity.

3.1. Dimensional accuracy

A general overview of the dimensional accuracy of each artifact replica is reported in Fig. 5, where a bar graph shows the 95th percentile values of the number of tolerance units n for the ISO basic sizes, while the grey horizontal bands represent the ranges of IT grades (Table 6). For any manufacturing process and machine, the dimensional accuracy is worse for smaller ranges of ISO basic sizes. High accuracy for small features (0-3 mm or 3-6 mm) requires that the machine is very precise. As the ISO size grows, the accuracy of the machine guarantees that larger features can be fabricated with better accuracy, therefore the bar chart normally shows the height of the bars in decreasing order from left to right, since the ISO ranges in the horizontal axis move from smaller sizes to larger ones [9, 10, 18, 19].

This decreasing trend can also be distinguished in the results for the Rover machine (Fig. 5) and is more evident for the G-Strong resin. The artifact replica made of the G-Strong resin has the worst dimensional accuracy. For the first two ranges of ISO basic sizes up to 6 mm, the dimensional quality of the G-Strong replica is IT16. For larger sizes, the accuracy improves for this replica and the grade IT14 is achieved for dimensions ranging from 10 mm to 50 mm.

The accuracy of the Rover printer with the other two resins is better than that of the G-Strong replica. An ISO IT15 grade is achieved with S-Hard and S-Clear resins for the smallest sizes, while the best accuracy of IT13 is reached for basic sizes in the range of 30-50 mm.

3.2. Geometric tolerances

The geometric tolerances of the replica features have been classified according to the Geometric Dimensioning and Tolerancing system (GD&T) system. The tolerances for the three resins are shown by the box plots in Fig. 6. In the left column of Fig. 6, the flatness of different types of planes is compared. In the analysis of the flatness, it is important to consider the 45° inclination of the artifact to the build platform during printing. Because of the manufacturing configuration, both horizontal and vertical planes of the artifact geometries are affected by the staircase effect of 3d printing.

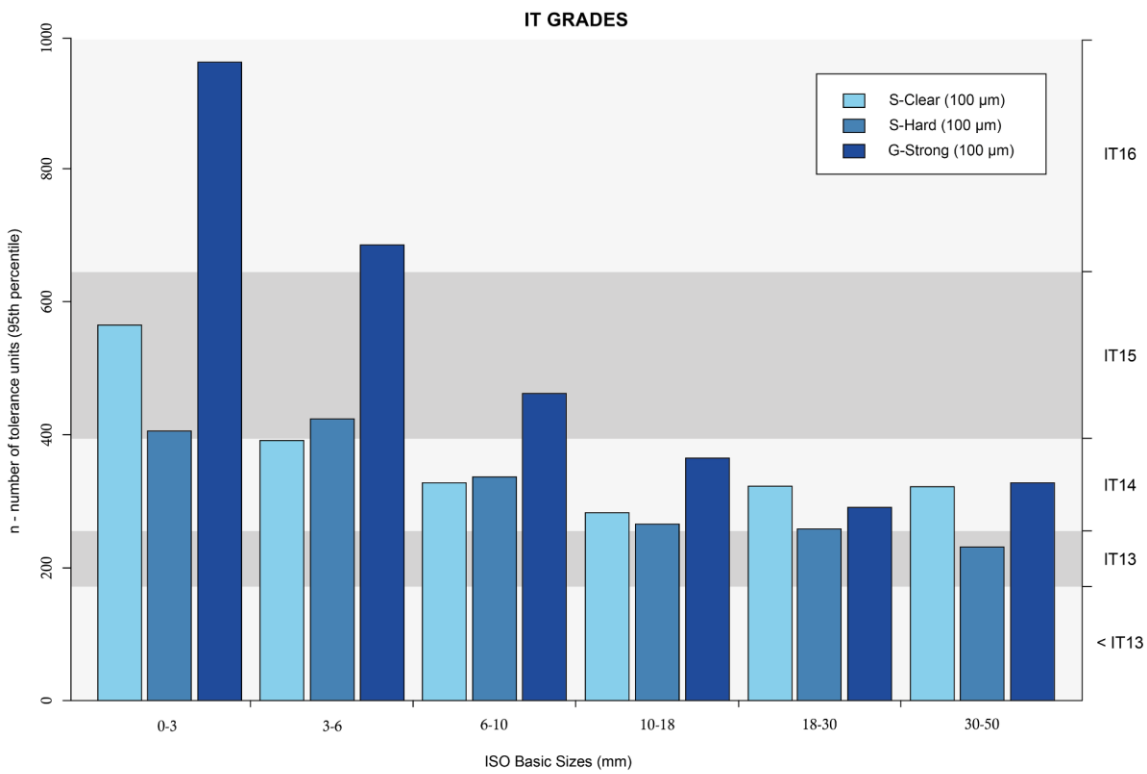

Fig. 5: Dimensional accuracy of the compared Sharebot resins in terms of IT grades for different ISO basic sizes.

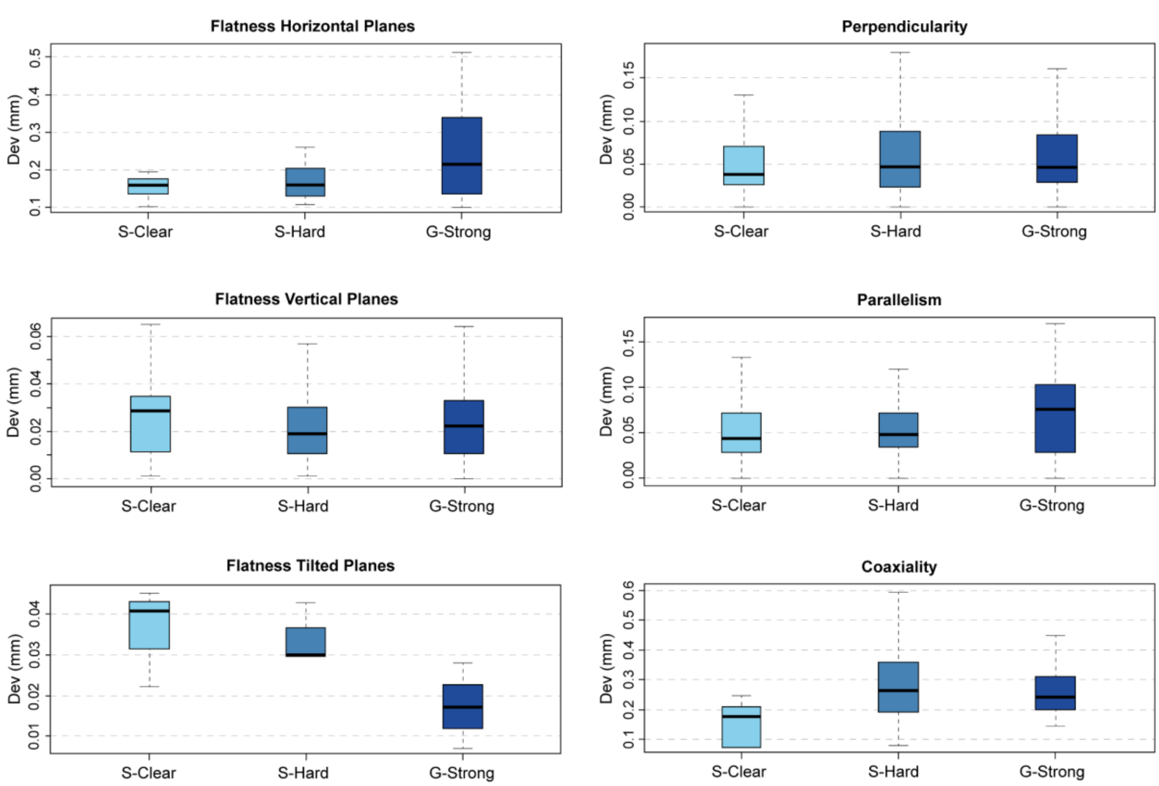

Fig. 6. GD&T deviations of the replicas for different resins using a lyer thickness of 100 microns.

The median value of the flatness of the three replicas is similar for the horizontal planes as well as for the vertical planes. Nevertheless, the flatness of horizontal planes ranges between 100 µm and 500 µm, while that of vertical planes is better and reaches almost 65µm in the worst case. While the range of variation of the flatness is very similar for the three resins in the case of vertical planes, the S-Clear replica has tighter tolerances than the others in the case of the flatness of horizontal planes. Among the three materials, the G-Strong replica has the worst tolerances for the horizontal planes but the best values for the flatness of the tilted planes. In the case of the tilted planes, the maximum value of the flatness for the G-Strong replica reaches almost 30 µm, while that of the other two materials exceeds 40 µm. Among the flatness tolerance, these results for the tilted planes are consistent with the part orientation during 3d printing. While vertical and horizontal planes have assumed an angle of 45° to the direction of layer addition, some of the tilted planes assumed a reduced inclination to the deposition of the layers. Therefore tilted planes were less affected by the staircase effect in 3d printing and better flatness tolerances were achieved for them.

Other types of geometrical tolerances are considered in the right column of Fig. 6. The three box plots in this column, shows the tolerances of parallelism for parallel planes, perpendicularity for perpendicular planes and coaxiality for the coaxial vertical cylinders CC and horizontal cylinders IP (Table 1). The results of the parallelism tolerance are comparable with those of perpendicularity. In the case of perpendicularity, the three replicas have a similar tolerance range with a maximum value close to 150 µm and a median value of about 50 µm. The median value of the parallelism tolerance is similar for S-Clear and S-Hard resins, while a higher median and range is observed for the G-Strong replica.

From the authors' experience [9, 10, 18, 19], the coaxiality tolerance is generally the worst that can be achieved in different 3d printing processes. This result is confirmed also in the case of the DLP process with the three resins by Sharebot. However, the S-Clear material outperformed the other two materials as far as coaxiality is concerned. The maximum coaxility error for the S-Clear resin is about 250 µm, while it's more than doubled for the S-Hard resin that shows a larger variability. In all cases, the coaxiality tolerance is larger for the horizontal cylinders IP than for the vertical cylinders CC.

3.3. Cost analysis

From the results of the previous benchmarking analysis, it can be stated that the use of the S-Hard resin represents the best compromise in terms of dimensional and geometric accuracy that can be achieved with the Rover printer when using a layer of 100 µm. Together with the previous quantitative results, printing costs can be evaluated.

For a simple and straight comparison among the three different resins, only the costs of machine and material are considered. These costs are used to compute the machine hourly rate and the cost of each replica, which depends on the printing time and the part weight (Table 8). Fixed costs that will be common to the three materials are not considered.

Table 8: Cost items

Cost item	Cost	Part weight	Supports weight
Rover machine	3050 €	NA	NA
S-Clear resin	199 €/kg	0.0174 kg	0.0134 kg
S-Hard	229 €/kg	0.0174 kg	0.0134 kg
G-Strong	140 €/kg	0.0174 kg	0.0168 kg

The machine hourly rate (HR) was estimated by assuming a depreciation period of 5 years. Considering 220 working days per year and 24-hour operation, since the machine can print overnight, with an utilization of 85%, the Rover hourly rate is calculated using the formula in equation 4, where M is the price of the machine in Euros, DP is the depreciation period in years and WD is the number of working days per year. With the above values, the Rover hourly rate HR is 0,14 €/h.

$$HR = \frac{M}{DP \cdot WD \cdot 24 \cdot 0.85} \tag{4}$$

The actual 3d printing times for the different resins are reported in Table 9 together with the calculated costs, that do not consider the energy consumption and related cost for the Rover printer. The material cost was computed from the weight of each replica and its support structure (Table 8) with an additional 10% to account for material shrinkage and the waste resin removed in the post-processing of the part.

Table 9: 3d printing costs of the three artifact replicas

Resin	3d printing time	Printing cost	Material cost	Total cost
S-Clear	10.33 h	1,4 €	6,74 €	8,15 €
S-Hard	6.72 h	0,9 €	7,76 €	8,67 €
G-Strong	8.05 h	1,1 €	5,27 €	6,36 €

The most expensive artifact replica is the one made of the S-Hard resin. Its cost is not much higher than that of the S-Clear replica but about 36% higher than that of the G-Strong replica.

4. Conclusions

In this work, an experimental benchmarking activity is presented to evaluate the dimensional accuracy of the DLP printer model Rover by Sharebot company. Three different Sharebot resins were used for the production of replicas of a reference artifact. The replicas were then inspected using a CMM to evaluate the dimensional and geometric accuracy, according to ISO IT grades and the GD&T system respectively.

The performance of the Rover printer in terms of dimensional accuracy for the three tested resins and basic sizes up to 30-50 mm is included in the ISO grades from IT13 to IT16. This result was achieved for a layer thickness of 100 microns, which was chosen to improve the productivity of the machine through a reduction of the 3d printing time. Benchmarking results show that better printing accuracy can be achieved for geometric features whose size is 6 mm or larger. Sharebot S-Hard resin performed better than the S-Clear and G-Strong materials. The quality of the S-Hard artifact ranged from IT15 for feature sizes smaller than 6 mm to IT13 for sizes between 30 and 50 mm. When comparing these results with previous studies about the accuracy of 3d printers [19], it can be highlighted that the same dimensional accuracy could be achieved using a filament printer and the same layer thickness of 100 µm.

As regards geometric accuracy, the use of S-Hard resin is the best compromise among the three materials. When considering also the costs, the S-Hard replica was the most expensive. Hence, it can be concluded that the user can get the best accuracy at the highest price with the S-Hard resin. The S-Clear resin could be selected only when a transparent part is needed because the reduction in costs to the S-Hard material is not significant. The G-Strong resin is the best solution for lower costs if printing accuracy is not a key factor.

The fabrication of the smallest features of the reference artifact seems to be the most critical aspect. The choice of the build orientation with 45° tilting to the Rover platform might have negatively affected the flatness of planes. This orientation might also have caused the collection of an excessive amount of uncured resin in the blind holes and slots while the part is drained out of the vat during the printing process (Fig. 3b and Fig. 3c). During the long printing time, the excess resin might have started its polimerization and partially cured on the part surface, reducing the effectiveness of the ultrasonic cleaning phase with a negative effect on the final dimensional accuracy of the replicas. However, further investigations are needed for assessing the influence of the build orientation on the benchmarking results. Therefore future studies should consider a smaller layer thickness and a different tilting angle of the replicas to the build platform to better characterize the printing accuracy of Sharebot Rover.

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