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Benchmarking of FDM machines through part quality using IT grades

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Abstract

The diffusion of Fused Deposition Modeling (FDM) was recently boosted by the expiration of the FDM patent and the subsequent worldwide development of low cost FDM machines by a huge number of small companies. In most of the cases, FDM machines are worth what they cost. Thus the performance of expensive industrial FDM systems is better than that of low cost machines, also known as 3D printers.
In this paper a benchmarking is carried out between a Dimension Elite™ by Stratasys and a 3D Touch™ by Bits from Bytes (BFB). The study and comparison is based on a reference part that was designed to fit into the building volume of most of low cost FDM machines. The part includes several classic geometries (planes, cylinders, spheres and cones) of different sizes to cover several ranges of basic sizes as defined by the ISO 286 standard. Geometric features appear both in the concave and convex shapes to account for all design possibilities. The proposed reference part allows to consider a higher number of features for each range of basic sizes with respect to other benchmarking models presented in the literature. Moreover the part does not require support structures for its production, allowing for manufacturing on 3D printers that come with a unique extruder. Replicas of the reference part are printed out of ABS (acrylonitrile butadiene styrene) material with different layer thicknesses using the compared machines. After inspecting the replicas by means of a Coordinate Measuring Machine (CMM), the dimensional accuracy of the compared FDM systems is reported through part quality using IT grades associated with the ISO basic sizes. GD&T values are also evaluated for some of the geometric features appearing on the reference part.

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Keywords: Benchmarking; 3D printing; Fused Deposition Modelling; IT grades; GD&T.

1. Introduction

Since 2008 after the expiration of fused deposition modelling patents, a great number of low-cost FDM machines have been developed worldwide. These machines are usually referred as 3D printers, most of which are open source systems whose development was sometimes driven by crowdfunding campaigns.

3D printers are sold at prices starting from some hundreds euros for kits that the user should self-assembly. Most of 3D printers come with a three axis architecture, a unique extrusion head and the building table and working volume are at room temperature. Two standard sizes are used for the plastic filament that measures around 1.75 mm or 3 mm in diameter. Usually the hot nozzle of the extruder can heat the plastic filament up to about 280 °C, while the nozzle diameter ranges from 0.10 mm to 0.70 mm. The cost raises when the 3D printer is equipped with multiple extruders, a hot table or a hot working chamber. The machine set-up is often manual in case of calibration operations or material change.

On the contrary, industrial FDM systems, that have been developed since the early 90s by Stratasys, come with a hot working chamber and advanced mechanic solutions for improved positioning accuracy and speed. They have at least two extruder heads, one for depositing the build material and the other for the support material, while the price starts from above 15,000 euros. The machine set-up is automatic and the material change is quite easy and fast since the filament is supplied in chipped cartridges.

With such a variety of FDM systems and commercial offers, there is the need to quantitatively compare the performances of different machines. The first impression that

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users get when visiting 3D printing fairs is that FDM machines are worth what they cost from the qualitative point of view of part surface accuracy and finishing.

Since the diffusion of first rapid prototyping (RP) systems in the late 80s, the lack of an international standard guideline for quantitatively assessing the performance and accuracy of RP machines has driven researchers to adopt benchmarking procedures. Benchmarking is carried out for comparing the performance of similar diverse systems (products, processes, machines, services and organizations). In the case of products and machines, the comparison is often based on real measurements because although technical characteristics are reported on datasheets, information is not always comparable or trustworthy of real performances of the compared systems.

As regards the comparison of RP machines, their performance is evaluated upon the dimensional and geometric accuracy of manufactured parts. Thus several reference artifacts with different geometries were defined and proposed in the literature to be used for benchmarking [1-12].

When dealing with the part's dimensional accuracy and tolerances, it is particular convenient to refer to the ISO standard IT grades [13, 14]. The IT grades allow for comparison of the geometric accuracy of different manufacturing processes as also reported by other studies [15-17]. Nevertheless only a few works [2, 8, 9, 11, 12] use the IT grades to summarize the results of a benchmarking study on the geometric accuracy of additive manufacturing (AM) or RP processes or machines. In addition to this, most of the proposed artifacts presents several different geometries that have similar sizes, thus it is impossible to cover different ranges of ISO basic sizes or the number of features for each range is low.

With the aim of overcoming those limitations, an innovative reference part is proposed in this paper for benchmarking purposes. The proposed reference part includes a higher number of features or dimensions for each range of basic sizes with respect to other benchmarking artifacts that have been proposed in the literature.

The following indications, that were defined by Moylan et al. [18, 19], are kept into account in the definition of the reference part's geometry:

- have a considerable number of small, medium and large features;
- not consume a large quantity of material;
- have many features of a 'real' part;
- have simple geometrical shapes, allowing perfect definition and easy control of the geometry;
- allow repeatability measurements;
- require no post-treatment or manual intervention (no support structures);
- not take long to build.

Nevertheless it should be noted that the last aspect concerning the building time depends on the layer thickness and on the machine speed, so it is not exclusively affected by part geometry.

For benchmarking purposes between an industrial FDM system and an entry-level 3D printer, two replicas of the reference part are printed out of ABS material using the compared machines. After inspecting the replicas by means of a Coordinate Measuring Machine (CMM), the dimensional accuracy of the compared FDM machines is reported in terms of IT grades associated with the ISO basic sizes of the reference part's geometric features and tolerances.

2. Benchmarking

2.1. The compared FDM machines

Two FDM machines are available at the Rapid Manufacturing Laboratory (RMLab) of the Department of Management and Production Engineering of the Politecnico di Torino. The former machine is the Dimension Elite$^{\text{TM}}$ (Fig. 1a) by Stratasys. This industrial FDM system has two extruders that are fed with the 1.75 mm ABS build filament and the soluble support material respectively. The working volume is 200 x 200 x 250 mm, the layer thickness can be set to 0.178 mm or 0.254 mm and the system costs about 20,000 euros.

The latter is an entry-level machine 3D Touch$^{\text{TM}}$ (Fig. 1b) whose production was stopped last year by 3D Systems to convert it to the new product line CubeX$^{\text{TM}}$. Disregarding small details, the 3D Touch$^{\text{TM}}$ is now available on the market at about 4,500 euros with the name CubeX Trio$^{\text{TM}}$ since its extrusion head is composed by three extruders. The extruders can be fed with 3 mm filaments, for deposition through a 0.5 mm nozzle into a working volume of 185 x 265 x 240 mm, with a layer thickness of 0.125 mm, 0.25 mm or 0.50 mm.

2.2. The reference part

The proposed reference part is designed to fit into the building volume of most of low cost FDM machines and its overall dimensions are 110 x 110 x 33 mm. Moreover the part does not require support structures for its production, allowing for manufacturing on 3D printers that come with a unique extruder without soluble support material.

As concerns dimensional inspection, the presence of simple classic geometries is imperative, since form errors and geometrical tolerances are defined on them [20]. Simple classic geometries (planes, cylinders, spheres and cones) are represented in the reference part in both concave and convex

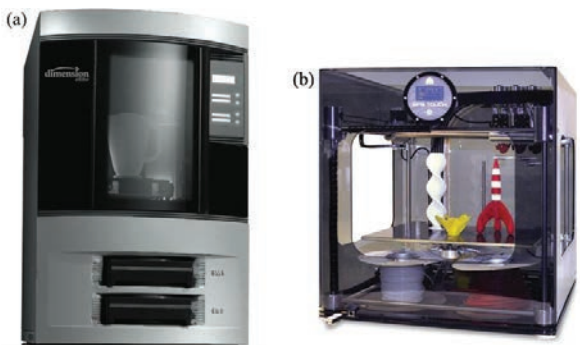

Fig. 1. The compared FDM machines: (a) Dimension Elite; (b) 3D Touch.

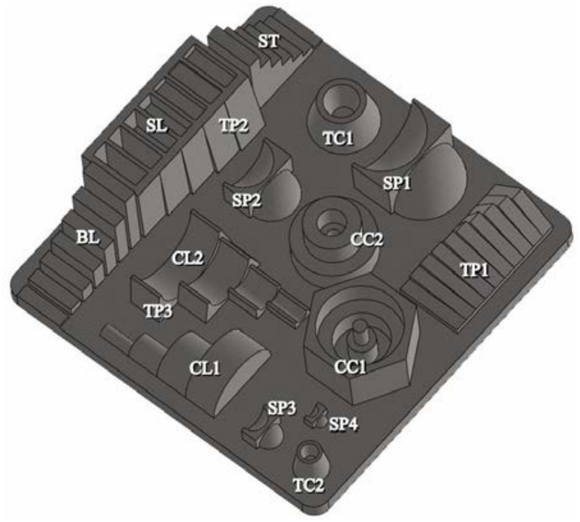

Fig. 2. CAD model and geometries of the reference part.

shapes accounting for different design opportunities (Fig. 2).

The change in the size of similar geometries is introduced for the measures to fit into different ISO ranges for the basic sizes 1 to 3 mm, 3 to 6 mm, 6 to 10 mm, 10 to 18 mm, 18 to 30 mm, 30 to 50 mm, 50 to 80 mm, 80 to 120 mm.

The following features appear on a 5 mm thick square base plate whose thickness is used to prevent deformation of the part during fabrication and after separation from the building platform of the FDM machine:

- *a set of seven rectangular blocks (BL)*: the blocks that have a 4 mm x 15 mm rectangular base are separated by each other and their height increases in the sequence 1 mm, 3 mm, 6 mm, 10 mm, 15 mm, 21 mm and 28 mm;
- *a set of seven rectangular slots (SL)*: the slots, that have a 5 mm x 15 mm rectangular base, are included into a 28 mm height rectangular block and their depth changes from 1 mm to 21 mm in the same sequence of the previous blocks (BL) with a repetition of the 3 mm dimension;
- *a set of seven steps (ST)*: the steps are connected to form a stair and their height decreases from 28 mm to 1 mm in the reverse sequence but same sizes of the blocks (BL);
- *two couples of coaxial truncated cones (TC1 and TC2)*: each set consists of an outer convex truncated cone and an inner concave truncated cone. The outer truncated cone of set TC1 has a major diameter of 20 mm, a minor diameter of 13.6 mm and it is 12 mm high. The coaxial inner truncated cone has an height of 10 mm, a major diameter of 10 mm and a minor diameter of 6.5 mm. The second set TC2 has a smaller size than the first set. The inner truncated cone of the second set has a major diameter of 5 mm, a minor diameter of 4 mm and it is 6 mm high. The coaxial outer truncated cone of set TC2 has an height of 9 mm, a major diameter of 10 mm and a minor diameter of 6.8 mm.
- *two sets of coaxial cylinders (CC1 and CC2)*: the first set CC1 is composed of two cylinders that measure 4 mm and 16 mm in diameter plus two blind holes that have a diameter of 8 mm and 24 mm. All these features have a height of 8 mm and the set is inscribed into a 16 mm high hexagonal prism whose hexagonal base has an edge length of 16 mm. The second set CC2 has the reverse shape but same size of the cylinders and holes of set CC1;
- *two sets of hemicylinders (HC1 and HC2)*: unlike the cylinders of sets CC1 and CC2, the hemicylinders have an horizontal axis. The first set HC1 consists of four convex hemicylinders that have a length of 10 mm, while their diameter decreases in the sequence 24 mm, 16 mm, 8 mm, and 4 mm. The four concave hemicylinders that compose the second set HC2 measure 10 mm in length and their diameter increases from 4 mm to 24 mm in the reverse sequence but same sizes of the features of set HC1;
- *four sets of quarters of spheres (SP1, SP2, SP3 and SP4)*: each set is composed of a concave quarter and a convex quarter of sphere that have the same size. The diameter of the spheres decreases from set SP1 to set SP4 in the sequence 4 mm, 8 mm, 16 mm and 24 mm;
- *three sets of tilted planes (TP1, TP2 and TP3)*: the first set TP1 is fan shaped and consists of 10 couples of planes. The inclinations of the two tilted planes within each couple are complementary. The ten couples fan out with an inclination to the part base plane increasing from 0 degrees to 45 degrees through steps of 5 degrees. The second set TP2 is located on the vertical face of the rectangular block of the slots SL. TP2 is used to appreciate changes in the inclination smaller than 5 degrees, as it is composed of five planes whose inclination increases in the sequence 0 degrees, 2 degrees, 4.5 degrees, 7 degrees, 9 degrees to the vertical plane. Last set TP3 consists of five planes that are located on the vertical face of the second set of hemicylinders HC2. The inclination of these five planes ranges from 70 degrees to 90 degrees to the part base plane with steps of 5 degrees. TP3 set is needed because in the fan-shaped set TP1 the planes with those inclinations do not have a sufficient extension as to allow for a correct measurement of the features.
- *several other vertical or horizontal planes*, that are parallel or orthogonal to the square base of the reference part.

The geometric features have been organised, located and oriented rationally to be representative for the evaluation of geometrical tolerances during the inspection phase. The staircase effect, that is typical of layer-by-layer manufacturing processes, can also be evaluated on different surfaces having diverse curvature.

In summary, more than eighty geometric features appear on the reference part. They allow for the measurement of over one thousand sizes and distances over the considered ISO ranges of basic sizes from 1 mm up to 120 mm, if one considers all measurable entities and surfaces. It should be also remarked that a unique configuration of the CMM probe with the axis orthogonal to the part base plane is sufficient to easily carry out the part inspection because enough space between adjacent features is provided for the approach and retraction of the probe using a tip diameter of 2 mm.

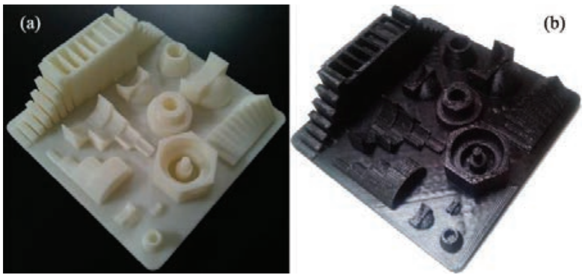

Fig. 3. Replicas fabricated by Dimension Elite™ (a) and 3D Touch™ (b).

2.3. Fabrication and inspection

A white filament was used in the Dimension Elite™ machine and the part was fabricated in approximately 7 hours adopting a layer thickness of 0.254 mm (Fig. 3a). About 120 cm^3 of ABS material were required to build the part, corresponding to around 1/10 of a brand new material cartridge.

In order to distinguish the two replicas, a black filament was instead used in the 3D Touch™ printer (Fig. 3b). The fabrication of the reference part took almost 18 hours with a layer thickness of 0.125 mm. About 80 gr of ABS material out of a brand new spool of 1 kg were used for part fabrication. Therefore for both machines, the amount of material required is acceptable. In both cases, the part was manufactured in the centre of the building platform, with the sets of blocks (BL), slots (SL) and steps (ST) aligned to the machine Y axis.

Replicas were not finished or polished, not to alter their surfaces or dimensions, since the as-manufactured condition should be considered for a correct benchmarking of the FDM machines.

After manufacturing, the replicas are inspected by means of a DEA CMM model GLOBAL Image 07.07.07 that has a declared volumetric length measuring uncertainty MPE_E according to ISO-10360/2 [21] of 1.5 + L/333 μm, where MPE is the acronym for Maximum Permissible Error and L is the measured length.

Three replications were made for the inspection of each replica and then average values are considered in the analysis of the results. At least ten inspection points were measured on each geometric feature and each replication took almost one hour.

3. Results of dimensional inspection

The results of the measurements of the geometric features of the replicas are used to evaluate the dimensional accuracy of the compared machines in terms of ISO IT grades [13]. The values of standard tolerances corresponding to IT 5 – IT 18 grades for nominal sizes up to 500 mm are evaluated through the standard tolerance factor *i* that is expressed in micrometres by the following formula:

$$i = 0.45 \cdot \sqrt[3]{D} + 0.001 \cdot D \tag{1}$$

where *D* is the geometric mean of the range of nominal sizes in millimetres (Table 1):

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

The IT grades are classified according to Table 2 by the number *n* of times that the tolerance factor *i* fits into the dimensional deviation. For example the grade IT12 corresponds to a minimum of 160*i* with *n* = 160.

For a generic nominal dimension D_{jn}, the number n_j of tolerance units is computed as follows:

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

where D_{jm} is the corresponding measured dimension.

For each feature's dimension or distance between features, the n_j value is computed and attributed to the range of ISO basic sizes to which the dimension or distance belongs. A certain distribution of numbers of units is so obtained for each ISO range for the two replicas. Within each range the *n* value corresponding to the 95th percentile of the distribution is assumed as the maximum dimensional error of the FDM machine to assess the accuracy through the IT grades consistently with previous studies in the literature [2, 15-17]. Results are summarized by the bar chart of Fig. 4.

Despite the smaller layer thickness used for part fabrication in the low cost 3D Touch™ machine, the dimensional accuracy of the industrial system Dimension Elite™ is better for most ranges of the ISO basic sizes. The difference is significative for smaller basic sizes up to 30 mm, whereas for bigger sizes the accuracy of the compared machines is similar.

Table 1. Ranges of ISO basic sizes and corresponding tolerance factor *i*.

Range		**Basic sizes**							
Above	D_1 (mm)	1	3	6	10	18	30	50	80
Up to and including	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 2. Classification of IT grades according to ISO 286-1:1988.

Basic size		**Standard tolerance grades**													
Above	Up to	IT 5	IT 6	IT 7	IT 8	IT 9	IT 10	IT 11	IT 12	IT 13	IT 14	IT 15	IT 16	IT 17	IT 18
1 mm	500 mm	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*

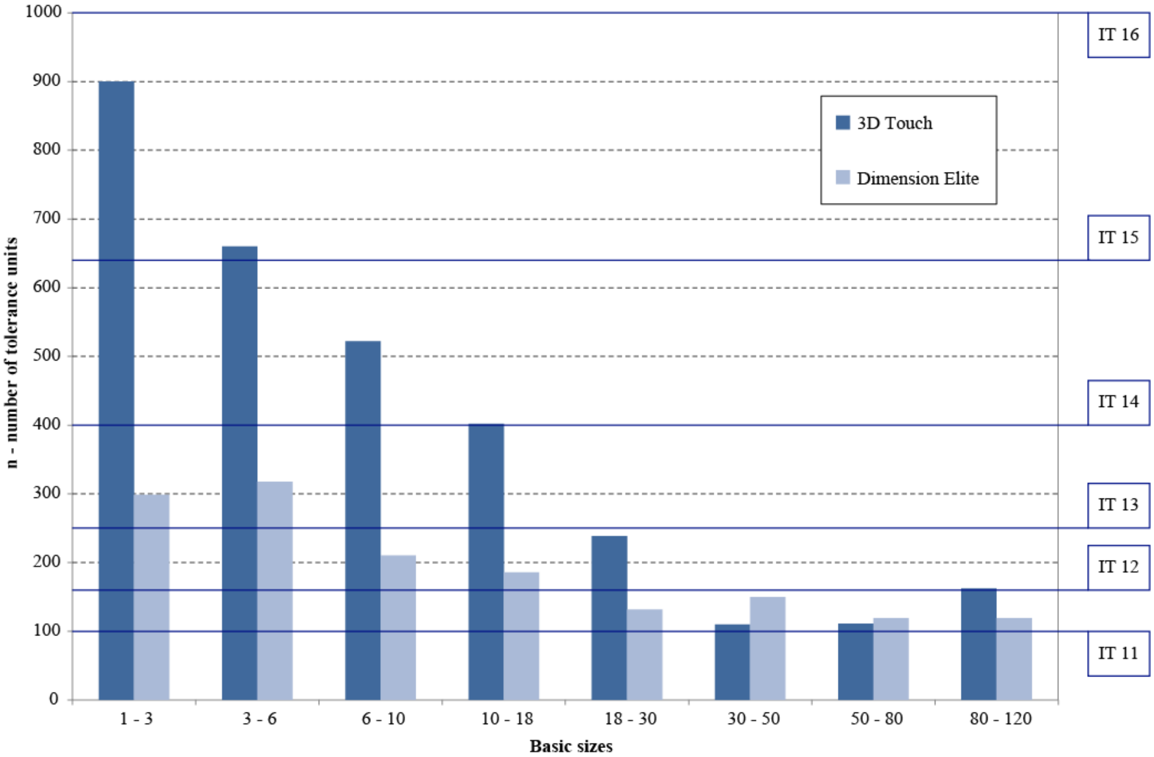

Fig. 4. Dimensional accuracy (95th percentile) of the compared FDM machines in terms of IT grades for different ranges of ISO basic sizes.

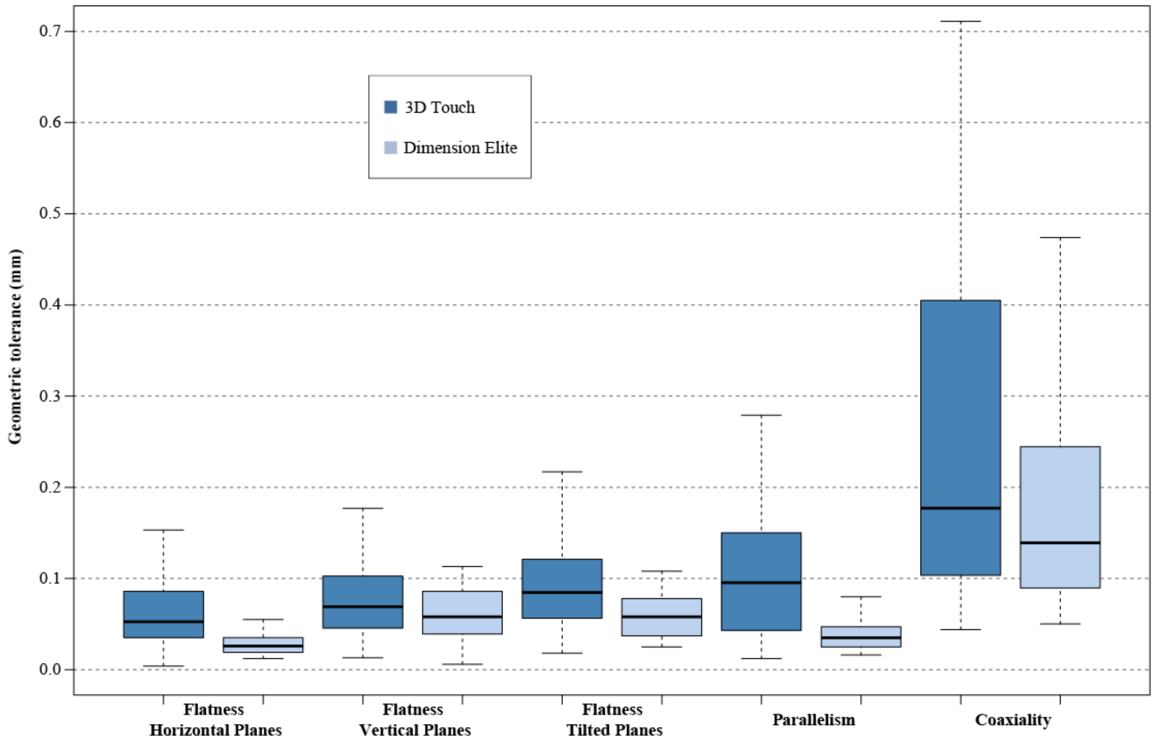

Fig. 5. Comparison of GD&T values for different geometric tolerances of reference part's features.

The IT grade for Dimension Elite™ ranges from IT 13 for smaller sizes to IT 11 for bigger sizes and it is always better or at least equal to the one of the 3D Touch™ printer for the same range of ISO basic sizes. The IT grade of 3D Touch™ worsens from IT 11 to IT 15 as the basic size decreases.

As concerns GD&T values (Fig. 5), the flatness is evaluated separately for horizontal planes, vertical planes and tilted planes to investigate the dependence on the staircase effect. Parallelism between couples of parallel planes and coaxiality of coaxial cones and cylinders are also considered.

The GD&T values confirm the results of the IT grades in terms of better accuracy of the industrial FDM system.The variation for the considered geometric tolerances is also much wider for the 3D Touch™ printer when compared to the one of the Dimension Elite™. As it could be expected, the flatness of horizontal planes is better than that of other planes because of the absence of the staircase effect. In fact, horizontal planes are fabricated within the same layer of material, while the presence of different layers affects the worse quality of vertical and tilted planes. For the Dimension Elite™ machine, parallelism tolerance is also good and has a small variation like the flatness of horizontal planes. Coaxiality of coaxial features is the worst tolerance for both machines.

4. Conclusions

The benchmarking activity carried out through the proposed innovative reference part highlights the greater geometric accuracy of the Dimension Elite™ machine when compared to the 3D Touch™ printer. The difference in the performance of Dimension Elite™ can be ascribed to advanced mechanic solutions, but also to the smaller diameter of ABS filament and extrusion nozzle which ensure a higher accuracy and detail for features of minor size. The hot chamber of that industrial FDM system also plays its role in reducing the shrinkage of deposited material layers that cannot cool down to room temperature, thus preventing part's deformation during fabrication.

As regards GD&T values, the median and interquartile range is very similar for both machines in the case of flatness tolerance of vertical planes. On these features, the smaller layer thickness adopted for the 3D Touch™ printer helps compensating the poorer geometric accuracy.

Over the first benchmarking results presented in this paper, the reference part will be used for comparing other FDM machines by fabrication of new replicas. The machine speed or the position and the orientation of the part into the machine working volume could be changed, not only for benchmarking purposes but also for optimizing the machine performances.

The proposed methodology has a general applicability and could also be extended to other AM systems that are used for production of metal parts.

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