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GEOMETRICAL AND DIMENSIONAL TOLERANCES OF SPECIMENS PRODUCED BY ADDITIVE MANUFACTURING AS FUNCTION OF PRINTING SPEED AND NUMBER OF PARTS PER CYCLE

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Abstract. Fused Deposition Modeling (FDM) is one of the various methods of Additive Manufacturing (AM). This method contains many manufacturing variables that affect the quality of the produced part such as nozzle temperature, printing bed temperature and printing speed. This paper aims to investigate the impact of the printing speed, and the number of specimens per cycle on the dimensional and geometrical tolerances of specimens produced by FDM. The specimen is designed with CAD software and manufactured with ABS filament using a GTMax3D CORE A3V2 3D printer. The printing speed velocities are 120 mm/s, 96 mm/s, and 72 mm/s and the 3D printing process is carried out in groups of 1 or 2 specimens per cycle. A CMM (Contura G3 RDS/XXT) is used for measuring different dimensional and geometrical features of the specimen. Results indicate that lower printing speeds generate better geometrical results, and medium-printing speeds with two specimens per cycle produce more accurate dimensional tolerances.

Keywords: Additive manufacturing, dimensional tolerances, geometric tolerances, 3D printing

1. INTRODUCTION

Additive Manufacturing (AM) is a technique in which a solid object, which was previously designed in a CAD software, is built by a series of overlapped layers. In this process, the machine heats the material to a near fusion temperature and the material is extruded through a nozzle (Cummins 2010). The machine software cuts the digital model into multiple thin layers and calculates the path that nozzle may follow to project the part.

Even though AM is very popular and great in process of scaling, one of the biggest hindrances for its consolidation as a competitive industrial manufacturing method is its inconstancies. According to Volpato et al. (2007), in the 3D printing process, many variables interfere with the results and in the mechanical properties of the object (dimension, toughness, elasticity, etc.). Some of those variables are the nozzle and table temperatures, printing path, printing velocity, and the material.

The AM technology can also improve the medical assistant for many people around the world. With its design range and diversity, the impact in health care is a matter of time. Dos Santos et al (2019), stated that AM can be used to produce intraosseous dental implants.

According to Peres et al (2021), the nozzle temperature also influences at the dimensional tolerances. In their paper, they experimentally analyze three different nozzle temperatures and compare the results. The temperature variation may bring improvements of 22% depending on the dimensional tolerance. However, each nozzle temperature provides and specific improvement in dimensional tolerances.

Zhang and Chou (2008) stated that among the effects of the major process parameters in FDM such as the road width, the layer thickness, and the scanning speed the scan speed is the most significant factor to the residual stresses followed by the layer thickness.

Using desktop 3D printers, Christiyan et al (2016) studied the impact of the printing speed in the layer thickness, as well as the layer thickness effects in the tensile and flexural strength values. They concluded that a low printing speed with low layer thickness gives a better bonding with the previous layer due to that it exhibited a better tensile and flexural strength. Therefore, the nozzle printing velocity also affects the specimens mechanical properties.

To reduce the geometrical and dimensional printing errors, AM companies developed their methods to obtain the ideal printing speed. Carrier (2018), as an example, created a parameters calculator to obtain an optimized printing velocity. The formula used by Carrier is simply the oblong area times the speed to calculate the volumetric output. The maximum value is acquired experimentally. In this calculator, the user inserts the nozzle diameter, layer thickness, and the used material values, then the calculator returns its maximum printing speed.

Even though the calculator brought significant improvements, this calculation is inaccurate because the calculator bases on ideal parameters. The results presented are correct in theory but not the reality of the 3D printings.

Khalil and Sun (2007) also developed a formula similar to the Carrier one. In their research, they determined that the printing speed is calculated following Equation 1:

$$Vn = \frac{4Q}{\pi \times Dn^2} \quad (1)$$

In this equation, Vn is the optimum velocity, Q is the Material Flow, and Dn is the nozzle diameter. It is demonstrated that a nozzle speed that is higher than Vn results in a smaller diameter material bead than the nozzle diameter whereas a nozzle velocity that is lower than Vn leads to a greater diameter material bead than the nozzle diameter. Neither of them is desired in because the final dimensions are in general different from the project dimensions, which, consequently, reduces the product quality.

In the food industry, Liu et al. (2017) stated that printing velocity has a critical influence on the results of the products. The food industry involves in its majority soft and viscous materials. Those materials have a significant runoff rate, this characteristic makes the printing velocity an even more impactful variable. Fast printing speeds overlap the material over an unstable base, which did not have enough time to settle and cool down. Overlapping weakens the structure, enlarging the runoff rate, which affect the product quality due to AM imperfections. Therefore, the study of the impact of printing speeds is necessary once there is an ideal printing speed in which the project dimensions have a minimum deviation from those ones from the original project.

Another printing variable is the number of parts per cycle. The reason for printing multiple specimens at the same cycle is to enlarge the time between the layers being added. In other words, when printing more than one object per cycle the nozzle takes more time to make the other specimen layer and to go from one specimen to the other. According to Rosa et al. (2019) the fabrication of multiple specimens per cycle impacts the mechanical properties of the part. This happens because the extra time that the nozzle takes to go through all the specimens, resulting in a higher temperature gradient between a layer and the next one. This effect is more significant when considering specimens with a lower infill percentage.

Besides those methods, there are other ways to reduce the geometrical and dimensional error in the AM. This paper proposes to investigate the influence of printing speed and number of parts per cycle in dimensional and geometric tolerances of the 3D printed parts.

2. METHODOLOGY

2.1 Specimen design

A specimen is designed using a CAD software (SolidWorks® 2019) and exported as a STL file. This file is sliced and the 3D printing G-code is generated with Simplify3D software. Figure 1 presents the designed specimen and its dimensions. The specimen has a simple geometry in order be cost-effective, easy to be manufactured and measured within a three dimensional coordinate measuring machine (3CMM). It has different topological geometries such as cylinders planes and holes.

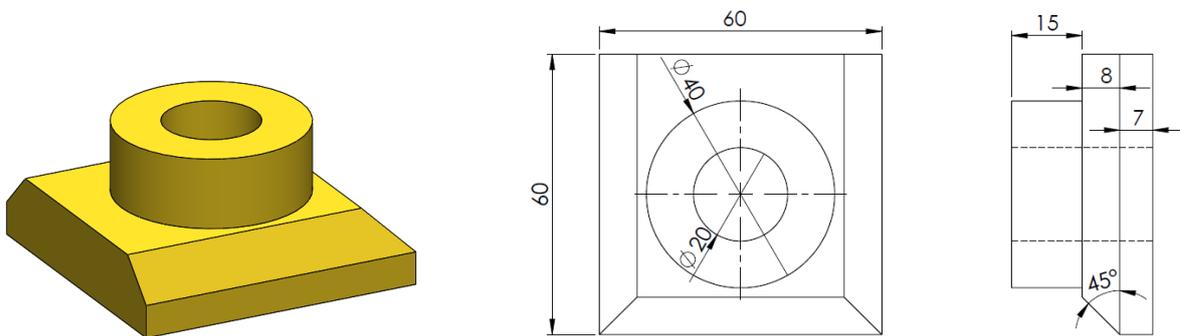


Figure 1. Isometric, upper and side view of the specimen.

2.2 Specimen manufacturing

Nine specimens are produced using a GTMAX3D CORE A3V2 3D printer using Acrylonitrile Butadiene Styrene (ABS) from 3D Fila. The 3D invariable printing parameters are presented in Table 1 and 3D variable printing parameters are presented in Table 2. Each group of three specimens is produced at 120 mm/s (specimens 1, 2 and 3), 96 mm/s (specimens 4, 5 and 6), and 72 mm/s (specimens 7, 8 and 9), respectively. Moreover, specimens 1, 4 and 7 are

manufactured separately, while specimens 2 and 3 are produced at the same printing cycle, specimens 5 and 6 are produced at the same printing cycle, and specimens 8 and 9 are produced at the same printing cycle (Table 2).

The 3D printing arrangement is presented in Figure 2. The distance from each other, is 5 mm and they are centralized in the X axis, and in the Y axis they are mirrored by the center.

Table 1. Invariable printing parameters for all specimens.

Setting	Parameters	Values
Quality	Layer thickness (mm)	0.12
	Reference print speed (mm/s)	120
Speed	Infill print speed (% of set speed)	50
	Outline layers print speed (% of set speed)	90
	Supports print speed (% of set speed)	
	Number of Top layers	10
Shell	Number of Bottom layers	5
	Number of Perimeter layers	5
	Printing bed temperature (°C)	110
Temperature	First layer nozzle temperature (°C)	250
	Other layers nozzle temperature (°C)	230
	Number of skirt layers	1
Skirt layers	Skirt offset from part (mm)	0.50
	Number of skirt outlines	2
	Room Condition	Room temperature (°C)

Table 2. Variable printing parameters for each specimen.

Specimen	Printing speed (mm/s)	Number of parts per cycle
1	120	1
2	120	2
3	120	2
4	96	1
5	96	2
6	96	2
7	72	1
8	72	2
9	72	2

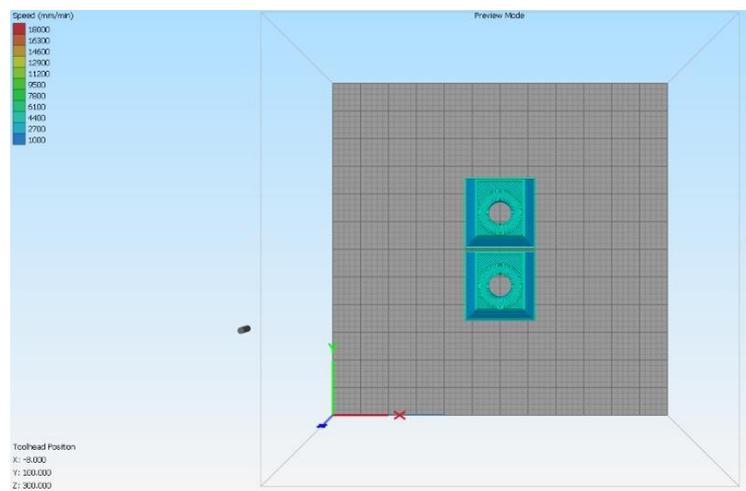


Figure 2 – Part arrangement in Symplify3D

2.3 Specimen measurement

The dimensions to be assessed are width, length, outer radius, inner radius, coaxiality between inner and outer cylinders, cylindricity 1 (inner cylinder), cylindricity 2 (outer cylinder), the angle between surfaces A and B, perpendicularity between surfaces X and Y, as well as the flatness of surfaces X and Y (Figure 3).

Measurements are carried out using a three dimension Contura G2 RDS/XXT Coordinate Measuring Machine (CMM). This machine uses Calypso® 5.2 and Dimension Volume® 1.6 softwares. The CMM is equipped with an RDS articulated headstock (Figure 4). This headstock touches the specimen and marks its coordinates. After marking the coordinates, the machine software measures the dimensional and geometric values. The CMM operated in a climatized room (20 ± 1 °C) and all specimens are acclimatized for 24 hours. The machine measures each specimen dimensional and geometrical parameters three times. The presented results are the average of the measurements.

According to the CMM calibration certificate (2012), the machine operates with a $0,2 \mu\text{m}$ resolution and a nominal range of $1000 \text{ mm} \times 2000 \text{ mm} \times 600 \text{ mm}$ in axis X, Y and Z respectively. The machine also have an expended linear uncertainty of $0,7 \pm L/278 \mu\text{m}$ for a coverage factor of $k = 2,00$ e 95% for each axis, where L is the measuring parts nominal range. The grope error is also $0,2 \mu\text{m}$

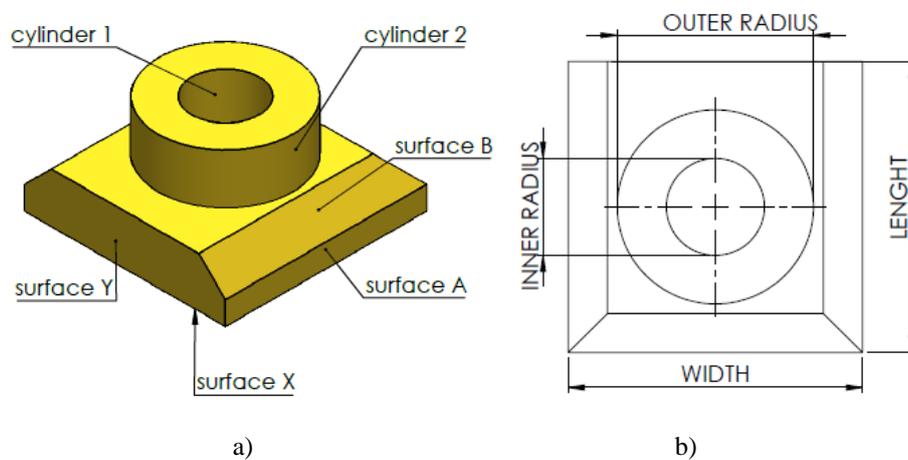


Figure 3. a) Geometric features, b) upper view dimensional

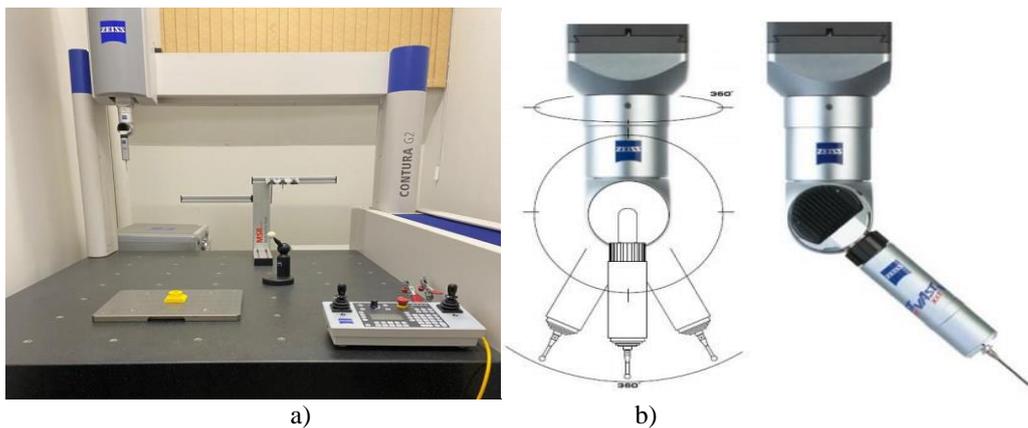


Figure 4. a) Contura G2 RDS/XXT CMM and b) RDS headstock.

3. RESULTS AND DISCUSSION

3.1 Base Dimentions

Base width and base length are straight-lined measurements. Therefore, there are no file representation problems. This means that the velocity and specimens per cycle analysis generates more precise and more realistic results (Figure 5). In all 3D printed specimens, except for specimen 6, length measurements have only $\pm 0.15 \text{ mm}$ deviation. There is an increase on overall width of the base when reducing printing speeds (Figure 5a). Although, this behavior is not repeated for base length measurements (Figure 5b)

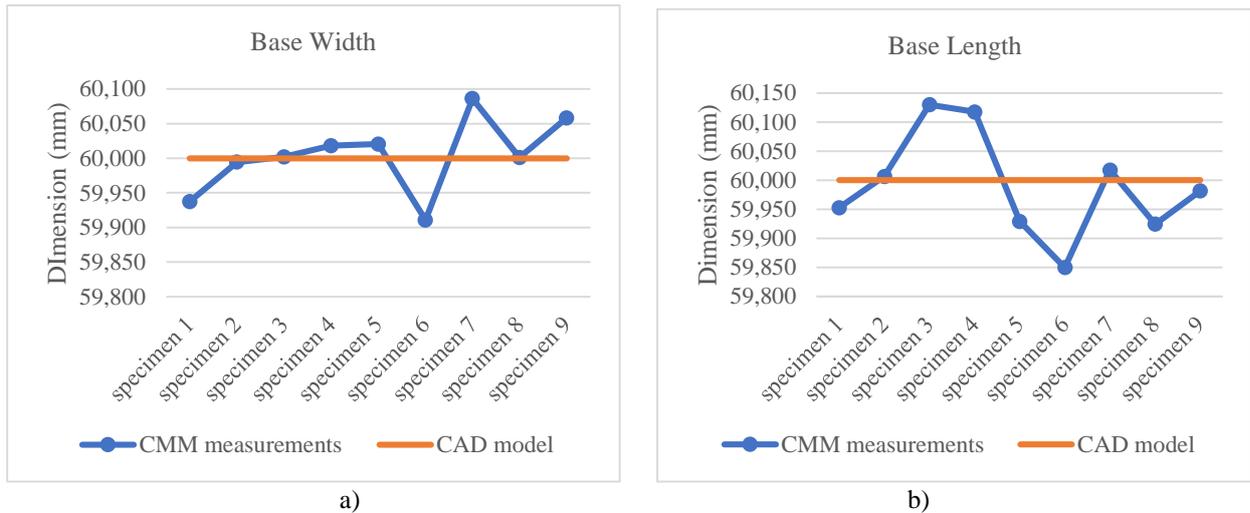


Figure 5. (a) base width and (b) base length measurements.

3.2 Inner and outer radii, cylindricity 1 and cylindricity 2

This leaking problem is also impactful for the cylindricity 1 (Figure 6c) and cylindricity 2 (Figure 6d) as well but the printing speeds has few impacts over this geometric measurement. An inconstant layer-by-layer extrusion produces an uneven surface, causing surface irregularities. In order to reduce this problem, lower printing bed temperatures are required. The inner and outer radius are also affected by the layer-by-layer extrusion (Figure 6a and 6b). However they are in a 0,05 mm range of deviation, differently from other dimensional features.

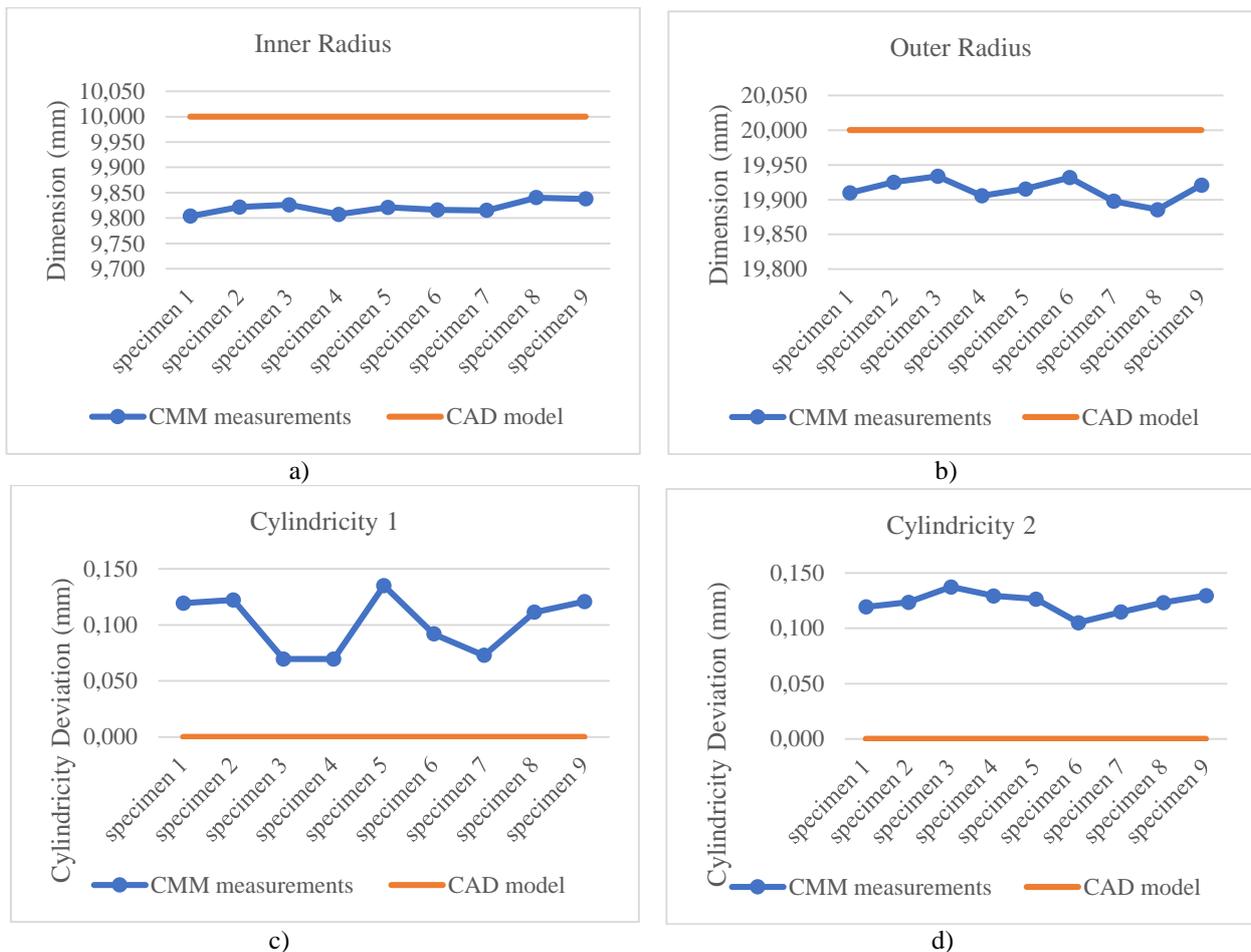


Figure 6. Radii and cylindricity of inner and outer cylindrical surfaces.

3.3 Surfaces X and Y Flatness

The surface flatness measurement is a cornerstone of this AM experiment because it is closely related to how the layers are added in after other. Every flatness measurement shows an error lesser than 0.1 mm, and, in some cases, smaller than 0.05 mm (specimens 5 and 7), which is below the printing height (0.12 mm), as presented in Figure 7a and 7b.

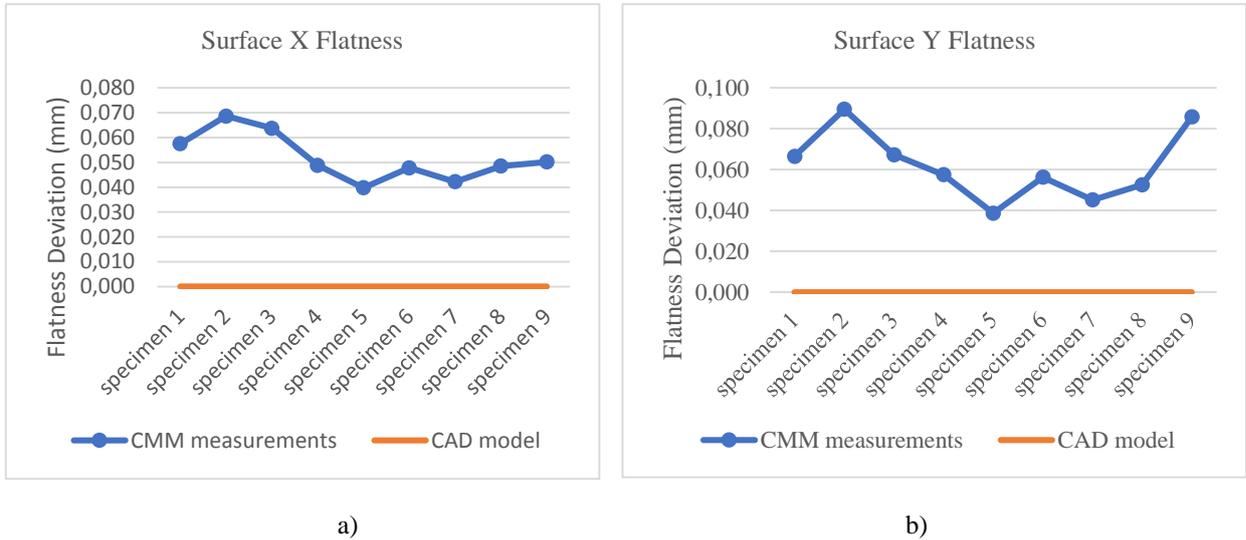


Figure 7. Flatness measurements of (a) Surface X and (b) Surface Y.

3.4 Angle between surfaces and perpendicularity measurements

With lower printing speeds (specimens 7 and 8) the angle between surfaces A and B has low deviation in relation to the project angle (45°). This is coherent because the material flux is very stable at low printing speeds. The number of parts per cycle has low influence in this parameter (Figure 8a).

In relation to perpendicularity, the deviation rises while the printing speeds are lower. In general, the perpendicularity deviations are lower for only one part per printing cycle. Hence, printing speeds and number of parts per cycle have few influences over the angle measurement and the perpendicularity deviation (Figure 8b).

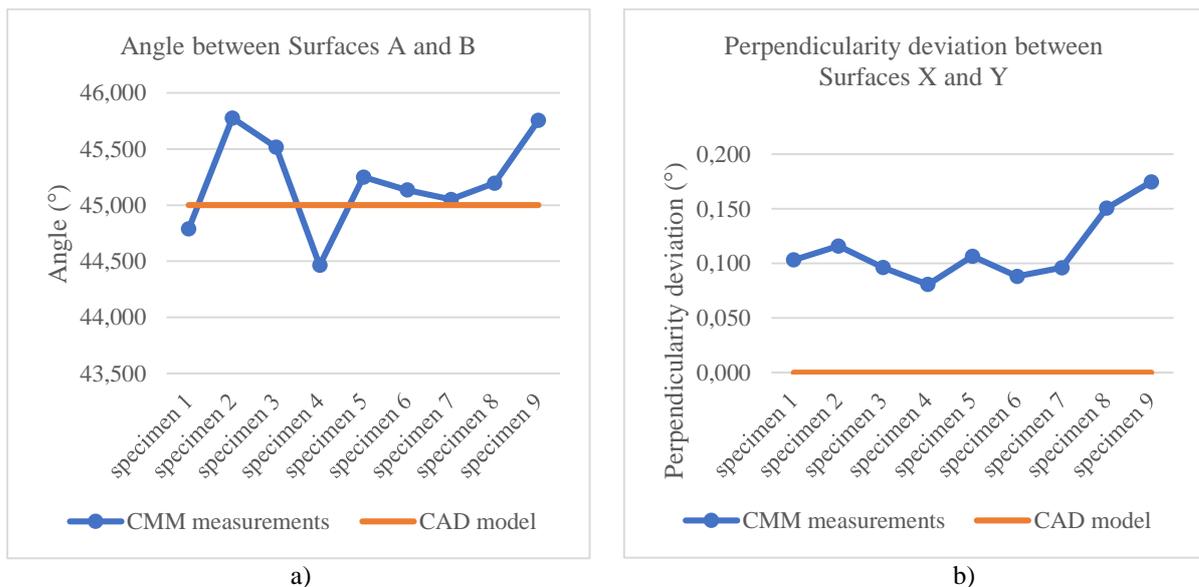


Figure 8. a) Angle between Surfaces A and B, and (b) perpendicularity between surfaces X and Y.

3.5 Coaxiality

Coaxiality measurements (Figure 9) are, in general, close to the 3D printing resolution (0.12 mm height). The number of parts per printing cycle has no particular effect in the parameters. Nevertheless, when lowering the printing speeds there is a reduction in the coaxiality deviations.

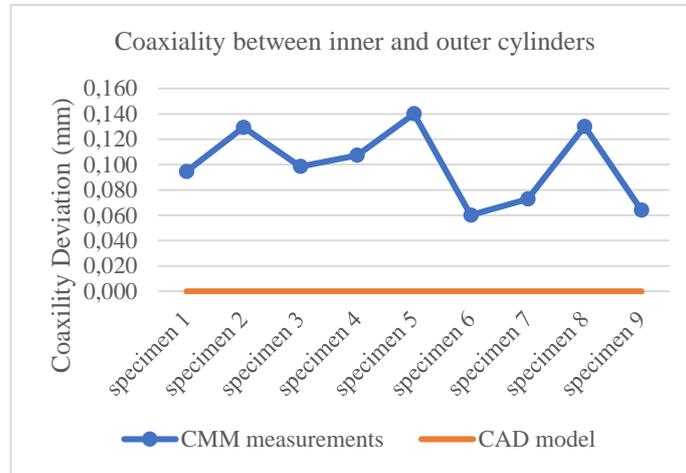


Figure 9. Coaxiality between inner and outer cylinders.

4. CONCLUSIONS

Additive manufacturing results are very dependent on the 3D printing parameters. The main objectives of this paper is to evaluate the influence of printing speeds and number of parts per printing cycle over dimensional and geometric features of ABS 3D printed specimens. Three printing speeds, one-part per cycle and two-parts per cycle are considered.

The specimen 7 generated the lowest deviations concerning the following measurements: base length (0.03% deviation), coaxiality between inner and outer radius (± 0.073 mm), angle between surfaces A and B (0.11% deviation) and flatness between surfaces X and Y (± 0.042 mm and ± 0.045 mm). The measurements of cylindricity 2 (± 0.115 mm) and perpendicularity between surfaces X and Y (± 0.096 mm) are among the second best results of all specimens.

Specimen 3 presented the lowest deviation for the outer radius measurement (0.33% deviation). Specimen 8 presented the lowest deviation for base width measurement (0.00016% deviation) and for inner radius measurement (1.6% deviation). Specimen 4 presented the lowest deviation for cylindricity 1 measurement (± 0.0696 mm) and for the perpendicularity between surfaces X and Y (± 0.081 mm). Specimen 6 presented the best cylindricity 2 measurement (± 0.105 mm).

72 mm/s printing speed with one specimen per printing cycle should be used to optimize geometrical features such as cylindricity 1, coaxiality between inner and outer radius, angle between surfaces A and B, and surface flatness. 72 mm/s printing speed and 2 specimens per cycle should be used better dimensional parameters such as base width and inner radius. 96 mm/s printing speed and one specimen per cycle parameters should be used for enhancing geometrical features such as cylindricity 1 and perpendicularity between surfaces X and Y. 96 mm/s printing speed and 2 specimens per cycle should be used for optimizing cylindricity 2. As conclusion, in order to enhance dimensional and geometric tolerances low printing speeds are preferred. These are preliminary results. More experimental tests with multiple parts per printing cycle are necessary in order to conclude whether this parameter has influence on dimensional and geometric tolerance in the additive manufacturing context. Other filament materials are also to be investigated.

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