

# COMPENSATION FOR DEVIATIONS ON CYLINDRICAL SHAPES MANUFACTURED BY 3D PRINTERS

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This paper compares deviations on cylindrical shapes between CAD models and parts created by additive manufacturing. These parts happen to have different dimensions, than their CAD models and even counterparts designed with working precision of 3D printers do not fit together.

These deviations are changing based on material and based on settings, but they are always in favour of overlapping fits. However, magnitude of these deviation seemed to be specific for every specific configuration. From this assumption we can make specific adjustments for every case, in order to get the most accurate dimensions for our parts from specific device.

In this study we are testing different dimensions and tolerances in order to find out, what adjustments in CAD model dimensions are necessary for creating lose fitting and tight fitting between two parts created on 3D printers from PLA material.

## KEYWORDS

Deviations, 3D printers, PLA, additive manufacturing

## 1 INTRODUCTION

Manufacturing prototypes using technologies like additive manufacturing is becoming easier and more affordable. Using 3D printers for these purposes is faster and it is allowing us to create shapes, which were not possible in the past. This technology has however limitation in final product accuracy, comparing to traditional manufacturing method like milling, where dimension corrections can be achieved directly on the device. [Holub 2016] In additive manufacturing process there are many factors like material contraction in cooling process, small chemical differences between materials, stiffness of the printer frame, correct settings, good calibration, settings in slicer and other. All these factors are contributing to deviations on final parts.

More advanced printers are nowadays advertising accuracy better than 0.02 mm. Parts after print have however bigger deviations, than this value. These deviations seem to be specific for every setting, but they are repeating themselves. From this assumption we can adjust dimensions in CAD model to achieve optimal dimension. This testing method should be universal for all devices and can be later implemented for further testing.

Researches comparing aspects on manufacturing by changing temperatures, material flow, infill density, colour of filament, strength of printed part etc., require changes in the default settings defined by manufacturer of the printer. [Banjanin 2018, Beniak 2019, Mendricky 2016, Valerga 2017]

From previous experience we knew, some devices are capable doing good quality prints from the default settings [Zmarzly

2018] and changes in the default settings are generally making other prints worse. This paper therefore propose solution which does not require making these changes.

## 2 TESTING

### 2.1 Conditions

We used Solidworks 2018 Student edition for making CAD parts, program Cura 4.3.0 for generating G-Code and 3D printer Ultimaker 2+. We used all default settings in all programs, what represents out of the box experience. Accuracy of the printer is 0.0125 mm in X/Y axis and 0.005 mm in Z axis. Nozzle diameter was 0.4 mm, print settings were set to 20% infill and medium quality. Bed of the printer was calibrated according to instruction manual. Because we had very good experience with previously printed parts on this device in areas like surface finish, strength etc., we did not change any settings in the printer or any programs. Program Cura shows only limiting setting option by default, list of some settings used in testing are in Tab. 1.. As material we used black and silver PLA from 3DW supplier.

Setting	Value
Layer Height	0.1 mm
Print Speed	50 mm/s
Infill Density	20 %
Infill Pattern	Grid
Material Retraction	Enabled
Flow of material	100 %
Print Temperature	200 °C
Bed temperature	60 °C

Table 1. Used settings

For measurement we used digital calliper model HG00962A and micrometre Somet from Technical University of Košice S11-38/24. Working precision of these measuring equipment is sufficient for our needs. Values shown in this paper are calculated from 10 measurements for each cylinder taken at random location. Values for inner diameters 1, 2, 3 and 4 mm were measured with microscope and Image Processing Distance Measurement method, rest is from digital calliper, however measurements with different devices shown similar results. All devices can measure with 0.01 mm accuracy. Standard deviation was calculated in program Excel trough function STDEV.P.

Most printed parts on this printer are cylinders or cases with cylindrical shape. Orientation of these parts is mostly set so that most cylinders have axis perpendicular to bed of printer, which is direction of z axis. Therefore, all tested cylinders were manufactured with their axis parallel with Z axis of the printer.



Figure 1. Ultimaker 2+

## 2.2 Testing sample

In the beginning we created CAD model with cylindrical shapes. We chose most common dimensions based on our previous experience. The outer diameters with size 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20 and 24 mm, and for the inner diameters 1, 2, 3, 4, 5, 6, 8, 10, 12 and 14 mm. All cylinders are located on pad. We also added small square as our referenced feature, if we needed additional measurements or if need compare multiple prints with each other and for checking accuracy of the printer in linear directions. [Cruz Sanchez 2014, Santana 2017]

As a time saving measure, we insert inner cylindrical features into outer cylindrical features and added small chamfers on top. The simple drawing of the designed part is shown in Fig. 2.. As our referenced model we used all default settings for exporting file into STL format.

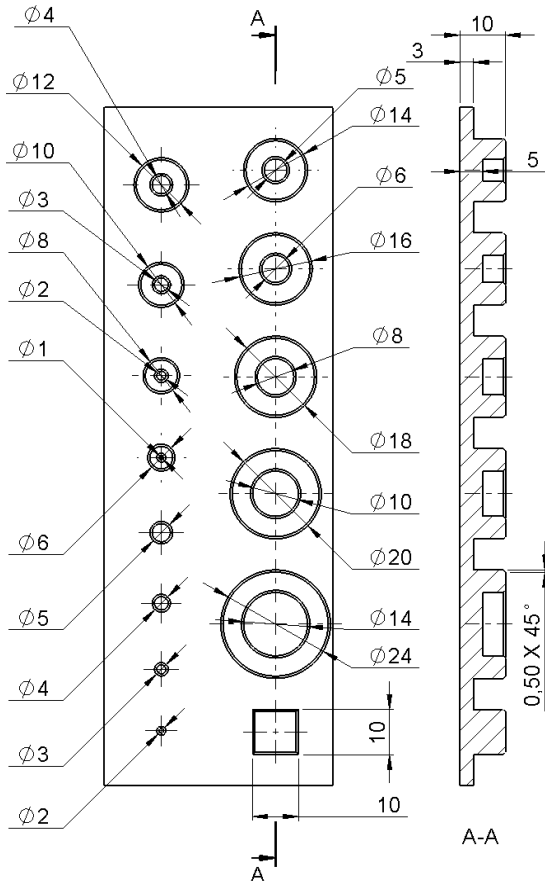


Figure 2. Drawing of testing sample

## 2.3 Referenced print

We printed first testing sample and leave it for 24 hours to cool down before measurement. Our testing square had 10.00 mm along long side and 9.99 mm along short side, which indicates, that printer can print required dimensions in the margin of accuracy of the printer. Because of wide range of measured values, we are including in Tab. 2. and Tab. 3. lowest and highest measured dimension.

CAD [mm]	Lowest value [mm]	Highest value [mm]	Average [mm]	Standard deviation
6	5.74	5.85	5.80	0.036
8	7.60	7.85	7.73	0.079
10	9.70	9.88	9.78	0.051
14	13.69	13.81	13.75	0.042

Table 2. Dimensions - inner diameters with default settings

Inner diameters 1, 2, 3, 4 and 5 have large irregularity in shapes making it impossible properly established points for diameter calculation under microscope and were too small for measurement with other instruments. Therefore, they are not considered in results. In additional testing we were trying to insert bolts M1-M5. Bolts were unable to fit into holes. These leaves assumption, that holes 1-5 mm are after manufacturing smaller in diameter comparing to CAD design.

CAD [mm]	Lowest value [mm]	Highest value [mm]	Average [mm]	Standard deviation
2	1.88	1.91	1.90	0.011
3	2.86	2.89	2.87	0.011
4	3.75	3.81	3.78	0.023
5	4.70	4.85	4.77	0.048
6	5.70	5.90	5.80	0.070
8	7.70	7.87	7.79	0.071
10	9.75	9.90	9.81	0.060
12	11.79	11.95	11.87	0.061
14	13.68	13.90	13.79	0.083
16	15.79	15.95	15.84	0.068
18	17.75	17.94	17.85	0.067
20	19.66	19.90	19.77	0.094
24	23.56	23.80	23.70	0.104

Table 3. Dimensions - outer diameters with default settings

After close inspection on final cylinders we can see that cylinders have in practise shape of polygons. These shapes have origin in CAD program, where STL files are generated.

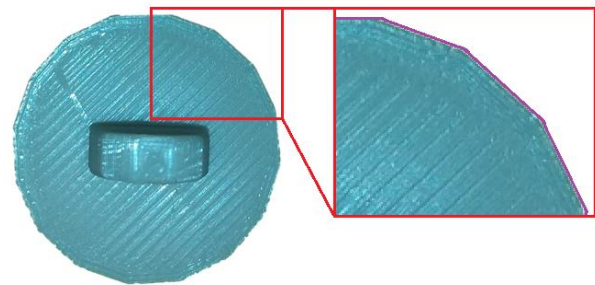


Figure 3. Polygons on parts

## 2.4 STL files

STL is file format widely used for transporting final parts between CAD program and G-code generating program. STL file does not support circular, or cylindrical shapes.

Main reason for deviations range has origin in exporting files from CAD program to STL file. Default value for circles approximation results into blocky cylinders.

In default settings, almost all CAD programs have default value for biggest allowed deviation set to high (0,074 mm deviation and 30° angle for SolidWorks).

Changing precision tolerance into smaller value results into much smaller triangles, which can increase accuracy of final parts. Way of approximation circular shapes into straight lines is also important for the direction of deviations. By default, Solidworks is making outer diameters and holes smaller than designed as shown on Fig 4.. This setting is good for holes, where we can by drilling achieve required diameter, but it is unsuitable

for shafts. Reversing setting is going to make holes bigger, which can result in loose fit.

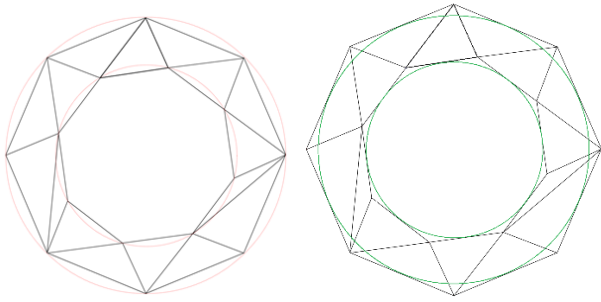


Figure 4. STL circle approximation

Final model is also going to have cylindrical shapes compiled by polygons, however size of straight lines is going to be smaller, than is smallest possible step for stepper motor. These adjustments increase file size from 100 kB to 4659 kB, which is not problem in this case, but can become problematic with more complex parts or large assemblies where slicer begin lagging or crashing while trying to manipulate large files, making it unusable.

After changing these tolerances on lowest possible value (0.0031mm and 0.5°), we printed same part again, and repeated measurements.



Figure 5. Printed cylinders before and after settings change

These changes increased cylindricity by elimination of polygons from previous parts as shown on Fig. 5.. Final dimensions are now much closer to design. We take measurements the same way as with first part, results are in Tab. 4. and Tab. 5..

CAD [mm]	Measured (average) [mm]	Deviation [mm]	Standard deviation
2	2.03	+0.03	0.015
3	3.03	+0.03	0.014
4	3.94	-0.06	0.015
5	4.95	-0.05	0.015
6	5.95	-0.05	0.014
8	7.95	-0.05	0.017
10	9.94	-0.06	0.011
12	11.96	-0.04	0.017
14	13.97	-0.03	0.011
16	15.95	-0.05	0.014
18	17.94	-0.06	0.017
20	19.95	-0.05	0.014
24	23.94	-0.06	0.017

Table 4. Dimensions - outer diameters with refinement STL settings

CAD [mm]	Measured (average) [mm]	Deviation [mm]	Standard deviation
3	2.94	-0.06	0.013
4	3.91	-0.09	0.015
5	4.96	-0.04	0.013
6	5.95	-0.05	0.014
8	7.95	-0.05	0.014
10	9.99	-0.01	0.015
14	13.96	-0.04	0.010

Table 5. Dimensions - inner diameters with refinement STL settings

Outer cylinders with designed diameter 2 and 3 mm have size corresponding with CAD (Fig. 7.), but majority cases are smaller in diameter.

Holes with diameter 1 and 2 mm have still large deviation in cylindricity what prevent from us to correctly choose points for circle measurement. Fig. 6 shows circle calculated from three selected points on the edge of cylinder, however on the left side is large gap, while on the top and bottom left edge of hole overlap drawn circle.

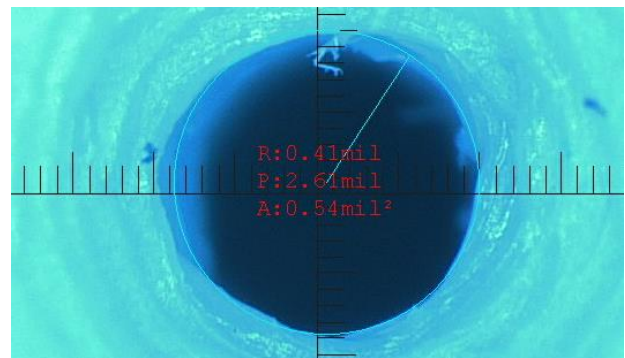


Figure 6. Measurement under microscope – hole 1 mm

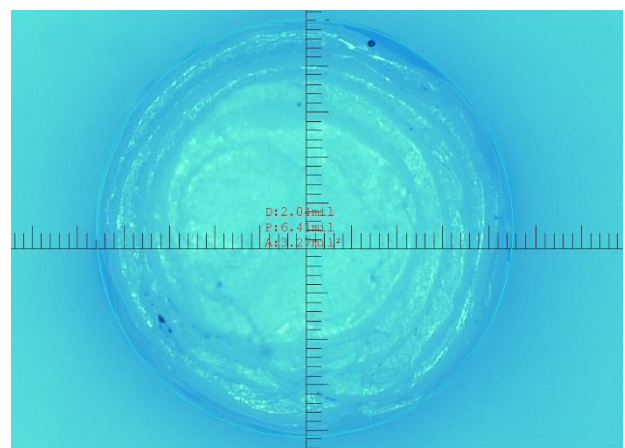


Figure 7. Measurement under microscope – shaft 2 mm

## 2.5 Adjustments in CAD program

For additional fitting in assemblies, we decided to create table for needed adjustment. Easiest option is to change dimension in CAD model on all cylindrical shapes that we need to be manufactured with increased requirement on precision. Reason for doing it in CAD is because of uniqueness of these deviations. This solution needs to be done for most cases, therefore as our reference correction we are going to use reverse value of mode in our deviation column. If mode will not be clear, we will use

median or average instead. In both cases correction needed to achieve intend dimension is +0.05 mm.

For different types of fitting we are now able define addition or reduction of diameter for achieving optimal result. Value for nominal fit represents addition to make cylinder with targeted diameter. Other type of fit assuming counterpart has already nominal dimension.

Type of fit	Inner diameter [mm]	Outer diameter [mm]
Nominal	+0.05	+0.05
Press	0	+0.1
Transitional	+0.1	0
Clearance	+0.15	-0.05
Big clearance	+0.2	-0.15

Table 6. Corrections

### 3 CONCLUSIONS

After testing different dimensions and different settings for printing, we discovered that main contribution for cylindrical deviations are in the export settings for STL files. By changing values for the tolerances in STL file we improved cylindricity on all cylindrical features. After these changes we repeated measurements, which reveal presence of smaller deviations. Majority of these deviations were in favour of smaller diameter than designed. Because we did not want changing other aspects of print, we decided to make corrections in CAD program by adding +0.05 mm for every diameter which is in contact with other part. We tried all these improvements on parts for multiple assemblies with success. We also recommended addition or reduction on diameter size, for achieving different type of fittings in assemblies.

As a result, we are now able to manufacture parts on the same equipment with smaller deviations while maintaining quality of print.

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