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QUALITY COMPARISON OF THREE FUSED DEPOSITION MODELING (FDM) PRINTERS AT DIFFERENT COST LEVELS

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QUALITY COMPARISON OF THREE FUSED DEPOSITION MODELING (FDM) PRINTERS AT DIFFERENT COST LEVELS

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ABSTRACT

The purpose of this study was to better define how quality in terms of surface quality, dimensional accuracy, consistency/repeatability, and total build time vary based upon 3D printers in different cost levels. One FDM printer was chosen at cost levels of entry level, intermediate level, and commercial level. A test block with various raised and recessed geometrical shapes was printed on each printer to analyze average surface roughness, dimensional accuracy, consistency/repeatability and total print time. When comparing the results, the most significant advantage with increased printer cost was the decrease in total print time. The commercial level printer, the Fortus 450, had a decrease in total build time to less than a fifth of the intermediate level printer, the 3D Platform printer. The 3D Platform decreased build time by nearly half as compared to the entry level printer, the MakerBotz 18s. Dimensional accuracy did not vary significantly between the printers, but the Fortus 450 did show the best consistency and repeatability. As far as surface roughness, the least rough measurements were taken on the test block side in the direction of increased layer height, while the measurements taken on the test block bottom/top in the direction parallel to the printer build plate, were roughest. When comparing surface roughness by printer there was not significant difference, but the Fortus 450 visually showed more consistent surface quality with minimal or no gap in the filament beads and also showed very consistent surface roughness measurements in three directions. Based upon the results when choosing a 3D printer as the cost increases, the driving factors appear to be total print time and consistency in accuracy and surface quality but in general, the best printer to choose is based upon how cost, surface quality, dimensional accuracy, consistency/repeatability, and total print time are ranked based upon the project.

CHAPTER 1 INTRODUCTION

Additive manufacturing, particularly three-dimensional (3D) printing, is a rapidly growing technology. Even though additive manufacturing technology is rapidly growing now, the early evolution of additive manufacturing technology actually began in the 1960s with efforts to solidify liquid photopolymers. The technology continued to evolve in the 1970s at the same time the inkjet printer also evolved. In the late 1980s, stereolithography (SLA) technology was the first additive manufacturing method to be commercialize (Wohlers, 2005). SLA is the process of solidifying liquid photopolymer by using an ultraviolet light beam to create each layer of the 3D object, one layer at a time. The object is then washed in solvent and subjected to ultraviolet light to cure (Swift, K. G., et al., 2013). Also in the 1980s fused deposition modeling (FDM) and selective laser sintering (SLS) were being developed for non-photopolymers but were not commercialized until later in the 1990s (Wohlers, 2014). FDM uses molten filament material to build the material layer by layer to create the 3D object (Swift, K. G., et al., 2013). Whereas SLS uses a powder material that is bonded layer by layer using a high powered laser beam (Swift, K. G., et al., 2013). In the late 1990s and 2000s, development for metals in additive manufacturing began to come into the picture. Selective laser melting (SLM) and electron beam melting (EBM) became available (Wohlers, 2014). SLM uses a laser to melt a powder material, which is very similar to SLS, except SLM does not just sinter or bond/fuse the powder together like SLS, SLM fully melts the material to create a homogenous object. EBM creates layers by melting metal powder using an electron beam, therefore the difference between EBM and SLM is EBM uses an electron beam instead of a high power laser beam (Larsson, M, et al., 2003). All of these processes continue to evolve today.

There are advantages and disadvantages to 3D printing in the commercial industry. One of the greatest advantages in 3D printing has been the advancement in rapid prototyping. Being able to 3D print a prototype in a matter of hours or days when it used to take months or longer, reduces the time for product development and also reduces development cost. Prototype tooling is expensive and can require a lot of time to make by traditional machining processes. Also, fit, form and function, can be easily altered with the 3D printing process after the design is tested since cost and time have been significantly decreased from traditional product development methods. Numerous design and build iterations can be done easily in a short amount of time to make a better product available to the consumer in a short amount of time and possibly at a lower cost, which is essential for success in the competitive market. Even though 3D printing has an advantage in the new product development process, there is also a disadvantage relative to regular production. 3D printing is best suited for production of small quantities. Traditional production methods are typically better suited for the production of large quantities. However, this is changing as 3D metal printers evolve and begin to be able to produce a large quantity of parts. Another disadvantage is the quality of the 3D printed parts. Significant improvement needs to be made in quality, such as surface roughness and accuracy of a 3D printed part.

With the rapid evolution of 3D printing, 3D printers are becoming more and more common in not only the commercial industry but also in the residential arena. 3D printers are becoming a hobby accessory and even a necessity in many households. And as the 3D printing technology has become popular, there is more and more need to better define the controllable parameters to create a better product. When it comes to 3D printers there a number of parameters that are controllable that affect the quality, durability and speed of the printed object. The 3D printer parameters that should be considered are infill, layer height, and printing speed. Infill, typically a percentage, represents the amount of material the object should be filled with. Increasing the amount of infill of solid material increases the strength of the object. However, there are tradeoffs, if one was to choose to maximize strength by maximizing infill of the object, then the cost of material, the weight of the object, and the time to print the object are increased. Layer height is the thickness of each layer printed. The thinner the layer, the higher the quality of the printed object. As with infill, layer height also has trade-offs. If one was to maximum quality by minimizing the layer height, then time to print the object could significantly increase. Last is the printing speed, the speed at which the head moves to print each layer of the object. Decreasing the printer speed, can increase the quality but also increase the time to print the object. Increasing speed, decreases the time to print but can also result in a low quality object. As described there are three common factors, quality, time, and cost that affect an object when defining 3D printer parameters.

Quality, time and cost are not only affected by the 3D printer parameters but can also be affected by the level of the 3D printer. For the purposes of this paper the three levels of printers are being defined as entry, intermediate and commercial level printers. Entry level being the most affordable and commercial being the most expensive. So how does the quality such as surface roughness and the accuracy of dimensional characteristics vary based upon the level of the printer?

CHAPTER 2 PREVIOUS WORK

Prior to 3D printers, prototyping a part was very costly and time consuming to produce. But because of the advances in 3D printing there is now a technology that can minimize cost and time to produce a part for rapid prototyping. However there is still a need for improvement in surface roughness and accuracy. Especially when it comes to parts that require accuracy, such a parts that make up an assembly, and without accuracy the fit and functionality of the assembly could be affected. Because of this need there have been many studies with a wide variety of approaches taken to analyze and improve surface roughness and accuracy of 3D printed parts.

As far as accuracy of 3D printers, one study compared accuracy of a 3D printed test block to printed parts in past studies. The results of the study conducted found that FDM and other printing processes still produce dimensional inaccuracies that can exceed +/- 0.300 mm in range (Relvas, et. al., 2012). Another study examined error in the x, y and z-direction of FDM printers and found accuracy decreased with increasing distance from the origin. (Bochman, et. al., 2015). Another focus as far as accuracy was to optimize printer parameters. A 3D open source printer test block and FDM printer test block were compared by using the grey relational method to determine the optimal parameter settings. This determined slice height of 0.254mm, raster width of 0.304 mm, and tip dimension of 0.254mm will improve the overall accuracy of FDM printed parts (Dixit, et. al., 2016).

Many studies have been done on both accuracy and surface roughness. A study analyzed accuracy of SLA test parts by recording measurements with a CMM and a surface profilometer to evaluate quality of the parts. The results summarized printer parameters that are major contributors to the accuracy of various types of dimensional, geometry and surfaces. The study also concluded the best printer settings to achieve the best accuracy by focusing parameters such as on layer thickness, resultant overcure, blade gap, hatch space, and position on the build plate. (Zhou, et. al., 2000). Another study compared dimensional accuracy and surface finish of the test blocks printed by SL, SLS, FDM and LOM printers. For dimensional accuracy, the SL printer showed the best accuracy for most of the dimensions measured, followed by LOM, FDM, and SLS. For surface roughness, SL provided the best surface finish, followed by LOM, SLS, and FDM. (Xu, et. al., 2000) A similar study found SLA to show the best accuracy and surface finish for SLA, followed by LOM, SLS and FDM (Mahesh, et. al., 2004).

There have also been studies that focus solely on surface roughness by varying different parameters. Surface roughness was analyzed by varying FDM printer parameters, layer thickness and infill, and also build orientation and post processing treatments. The lowest surface roughness recorded in the study was at YZ plane at 0 degree orientation with 100% infill and a layer thickness of 0.30mm, the largest layer thickness analyzed in the study. Production time was reduced when infill was reduced to 20% fill at XY plane at 0 degree orientation. For post processing treatments sand paper was found to reduce production time and cold vapor was found to lower the cost. (Chaudhari, et. al., 2018). Another study researched five printing parameters to verify the relationship with surface roughness of a 3D printed part. The five parameters considered were layer height, printing path, printing speed, temperature and wall thickness. It was found the surface roughness was most influenced by layer thickness and wall thickness. Layer height of 0.15 mm and 0.25 mm were selected and wall thickness of 1 mm and 3 mm were selected. The lower layer height and wall thickness selections resulted in the best surface roughness. As both parameters are increased, it would be expected for the surface roughness to worsen. No evidence of influence was found for printing path, printing speed and temperature. (Perez, et. al., 2018)

Some approaches have been taken by applying analytical models to improve surface roughness. In this study, analytical models were evaluated to be able to optimize parameters prior to printing. And a hybrid model was developed to further optimize surface roughness prior to printing (Vahabli, et. al., 2017). Also surface roughness was evaluated based on analytical models, Byun, Ahn, Campbell, Mason and Pandey. Each model was evaluated at different orientation angles and the Mean Absolute Percentage Error (MAPE) was calculated to determine the best model to predict surface roughness at different orientation angles. Overall, the Pandey model provided the best estimate for the prediction of the surface roughness. (Rashmati, et. al., 2015). Another study researched optimizing printing parameters to optimize surface finish so post processing steps are not required. A regression model was created for plane, concave and convex surfaces related to parameters layer thickness, inclination, and rotation along the z-axis and the design parameter radius. Inclination was found to have more influence on surface roughness in plane, concave and convex surfaces. (Martinez, et. al., 2012).

Additional research has also been done on build orientation of 3D printed parts. A study compared the differences in quality and cost of four rapid prototyping processes, SL, SLS, FDM, and LOM. And determined the optimal orientation of a printed part for each of the different rapid prototyping processes and concluded the optimal orientation is different for each of the rapid prototyping processes (Xu , et. al., 1999). Another study, analyzed surface roughness, but also kurtosis and skewness were used to define the surface quality for FDM printed test parts at various thickness layers and part orientation angles. In this study build orientation was considered the most critical factor to influence kurtosis, skewness and average surface roughness (Mohamad, et. al., 2017). A model was also developed to optimize the build orientation to minimize post-machining (Ahn, et. al., 2006). And this model was further developed in a study that proposed another parameter, Pa, to evaluate surface quality instead of average surface roughness, Ra, alone. Average surface roughness alone is not sufficient from theta, the angle defined from the x-axis, greater than 0 until approximately 33 degrees, therefore a model was developed to estimate Pa to determine surface quality for not only this range of theta but the entire theta range (Di Angelo, 2017). Research was also done to analyze minimizing error on circularity of FDM parts by investigating the relationship of the parameters fill density, and horizontal and vertical orientation of a test parts. A test part in the shape of a ring was designed to test for circularity error at varying fill density, horizontal orientation and vertical orientation. It was determined at 50% density, and 0 degree horizontal and vertical orientation provided the minimum amount of circularity error for the inner and outer diameter of the ring (Eswaran, et. al., 2018).

Due to the need to improve surface roughness on 3D printed parts, research is also being done on post processing procedures. Surface roughness of FDM parts were compared for different cycles and durations in an acetone vapor bath. The optimal cycle and duration to improve surface roughness was determined to be 3 cycles for 15 seconds (Lalehpour, et. al., 2018). Another study also found that when a test part made of acrylonitrile butadiene styrene

(ABS) is exposed to chemical vapor for a duration of 20 seconds, the part showed a smoother and harder surface as compared to an unexposed test part. (Chohan, et. al., 2018).

One area of study that has been only minimally investigated is energy consumption of 3D printers. One study investigated not only surface roughness but also energy consumption of FDM printers. It was determined that layer thickness was the most influential parameter on surface roughness and energy consumption. These were followed by printing speed and infill ratio for surface roughness and the opposite for energy consumption, infill ratio then printing speed (Peng, et. al., 2018).

Based upon literature, there is a wide range of studies that have been accomplished to improve surface roughness and accuracy. There have been analytical and experimental studies looking to optimize printer parameters, build orientation, and even developing post processing procedures to minimize surface roughness and accuracy. However, minimal research was found on comparing surface roughness and accuracy of test parts from various 3D printers, the focus of this paper.

CHAPTER 3 METHODOLOGY

As mentioned previously Fused Deposition Modeling (FDM) is a type of additive manufacturing that was developed in the 1980s. It was created by Scott Crump and later Crump commercialized FDM in the 1990s with the company he founded, Stratasys Inc. FDM is a trademark name of Stratasys Inc. Fused Deposition Modeling is where material, plastic filament or metal wire, is molten when extruded through a heated nozzle and the material is deposited on a printer build plate where the material cools. The printer stacks one layer of material at a time to create the 3D object (Swift, K. G., et al., 2013). The RepRap (Replication of Rapid Prototyping) project developed the term FFF, Fused Filament Fabrication. FFF another name for FDM, however FFF is a non-trademarked name (Ramírez , A, et al., 2019).

Based upon 3D printers available for use, the three printers chosen for comparison were the MakerBotz 18s (entry level), 3D Platform (intermediate level) and the Fortus 450 (commercial level). The MakerBotz 18s and the Fortus 450 are FDM printers, while the 3D Platform is a FFF printer, as shown in table 1. FDM printers are one of the more popular printer types chosen due to being more user friendly.

Various filament materials can be used on a FDM printer but the most common filament materials are thermoplastic resins. The filaments are formed into a wire that can be used to feed the filament into the 3D printer. The two most common types of thermoplastic resin filament materials are ABS (Acrylonitrile Butadiene Styrene) and PLA (Polylactic Acid). Other thermoplastics resin filaments materials such as PC (polycarbonate), ABS/PC blend and PEI can also be used. For the purpose of this paper, a combination of ABS and PLA was used, dependent on what filament material was allowed for each printer available for comparison.

The general 3D printing process starts with the creation of a 3D model in CAD or modeling software. The slicer software, which is dependent on the printer manufacturer, uses the CAD model to create a Standard Tessellation Language (STL) file format that the 3D printer is able to use to print the 3D object layer by layer. During this process printer parameters, such as infill, raster angle and layer height can also be adjusted. Raster angle being the direction of which the filament material bead is laid by the nozzle in the x-y plane. A 90 degree raster angle is when the filament bead is laid parallel to the x or y axis, where as a 45 degree raster angle is when the filament bead is laid in a diagonal direction as shown in figure 3.1.

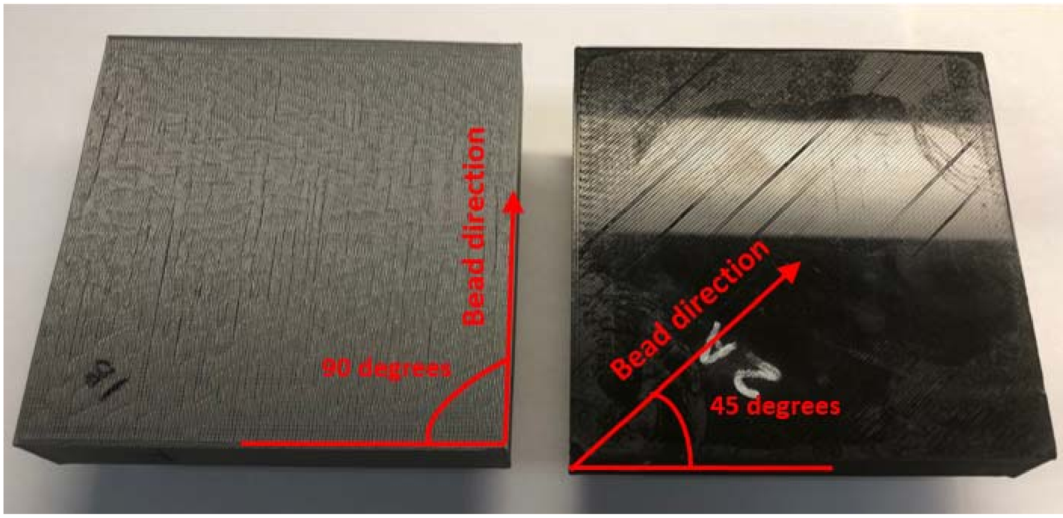

FIGURE 3. 1 Raster angle comparison of 45 and 90 degrees on the bottom of two test blocks

For this paper, a test block was designed in a CAD program with various common geometric and dimensional features to evaluate surface roughness and accuracy of three 3D printers. The 3D printers summarized in table 3.1 were chosen to compare three cost ranges of printers, which includes a low cost (entry level), a mid-ranged cost (intermediate level) and a high cost printer (commercial level).

TABLE 3. 1 Comparison of printers

Printer	Type	Heated Build plate	Heated Chamber	Estimated Cost
MakerBotz18s	FDM	No	No	$6,500
3D Platform	FFF	Yes	Not enclosed– N/A	$30,000
Fortus 450	FDM	No	Yes	$230,000

Each test block was printed with a recessed and a raised cone, hexagonal prism and cylinder, as shown in figures 3.1-3.5. Three test blocks were printed at the same time on each of the three printers for a total of nine test blocks. The initial methodology was to print each test block one at a time on the same build plate location to minimize error that could be created on a test block being printed on a different location of the build plate, however the initial print was done with all three test blocks printed at the same time but at different locations on the printer build plate. The printer build plates were large enough to allow for the printer operator to arrange multiple test blocks on the build plate at a time to test multiple instances of the test at once. Due to printer availability the test blocks were not able to be reprinted. Therefore all three test blocks were printed at the same time for each printer. Figure 3.6 shows the layout of the test blocks on the build plate, along with the orientation of the test block. The base of the test block is printed flat on the build plate therefore no support structures were required.

Layer thickness, infill and build orientation were the printer parameters chosen to keep consistent as much as possible throughout the study. Orientation was the same for all test blocks, bottom of test blocks were parallel to printer build plate. Infill and layer thickness were fixed as much as possible. The printer settings are summarized in table 3.2. However, the raster angle differed for the Makerbotz 18s due to being printed at a 90 degree raster angle versus a 45 degree raster angle for the other two printers. Raster angle mostly influences mechanical properties of the test block and has minimal influence on surface roughness and accuracy. Total print time was also recorded for each of the printers, where all three test blocks were printed at the same time on each printer.

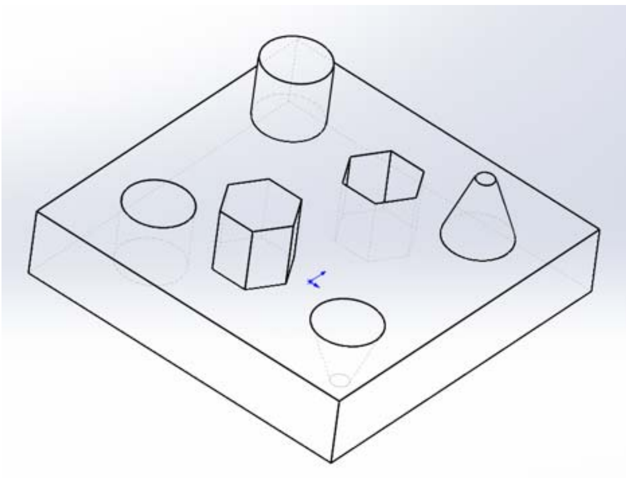

FIGURE 3. 2 Test block

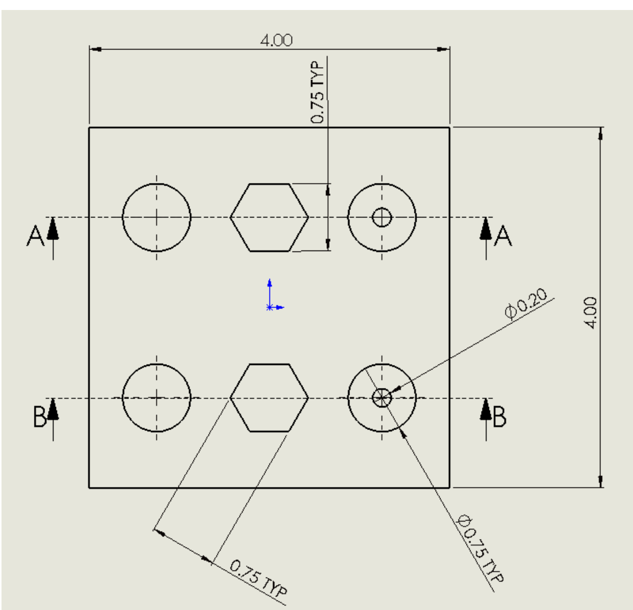

FIGURE 3. 3 Top view of test block. Dimensions in inches

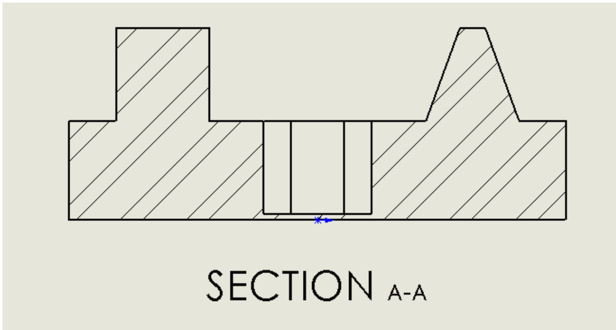

FIGURE 3. 4 Cross section A-A of test block

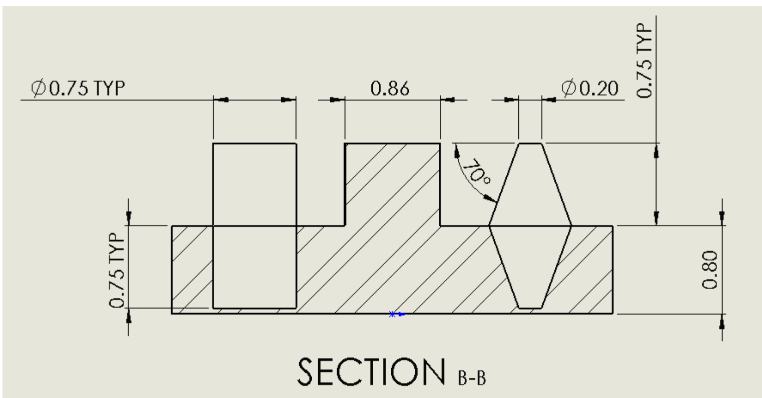

FIGURE 3. 5 Cross section B-B of test block. Dimensions in inches.

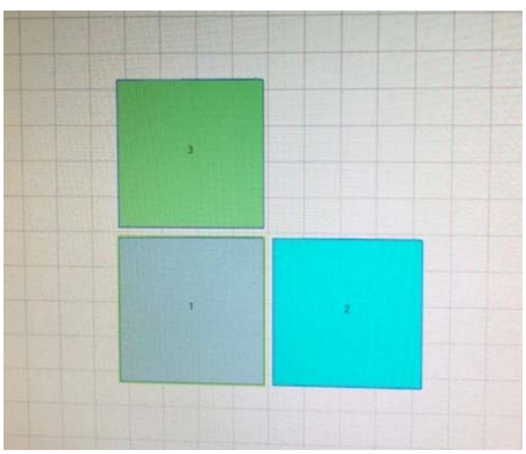

FIGURE 3. 6 Test block layout on printer build plate

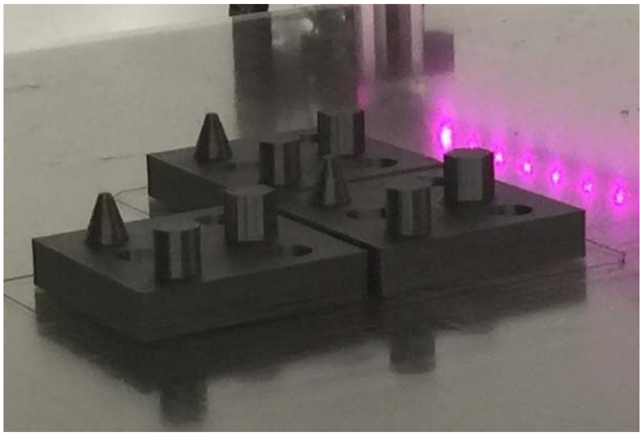

FIGURE 3. 7 Picture of three test blocks on 3D Platform printer build plate

TABLE 3. 2 Printer Settings

Printer	Material Used	Nozzle	Infill	Layer Height	Raster Angle	Run time
MakerBotz18s	PLA	0.4 mm	40%	0.010 in (0.254 mm)	90 deg	15h 19m
3D Platform	PLA	0.6 mm	40%	0.25 mm	45 deg	6 h 53m
Fortus 450	ABS	T16	Sparse- double dense setting (Approx 54%)	0.010 in (0.254 mm)	45 deg	6 h 24m

Each test block was measured for surface roughness using a Mahr MarSurf LD 130. Average surface roughness, Ra, was recorded for each test block. Initially surface roughness measurements were taken on the front side as shown in Figure 3.8 of all nine test blocks. Measurements were then taken on the bottom of all nine test blocks near the center for a 1-inch distance. Since the raster angle of the Makerbotz 18s was at 90 degrees, the direction of the surface roughness measurements were taken perpendicular to the filament bead laid by the nozzle, which is parallel to the front side as shown in figure 3.8. For the 3D Platform and Fortus 450, measurements were taken diagonally from the raised cone to the recessed cylinder, also perpendicular to the filament bead laid by the nozzle, since the raster angle was 45 degrees. Direction of the surface roughness measurements are shown in figure 3.8 below.

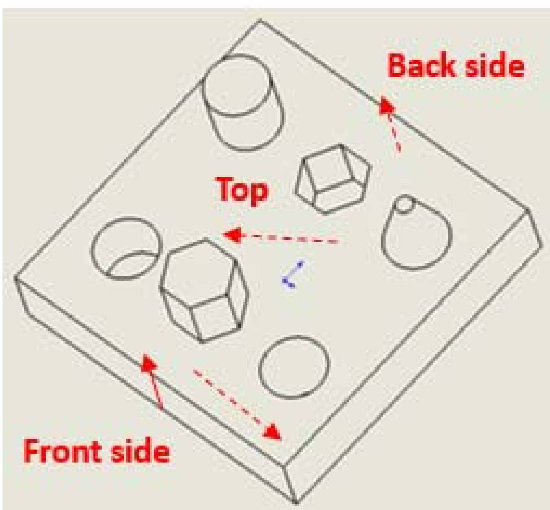

FIGURE 3. 8 Direction the surface roughness measurements were taken on each test block

The front side location and bottom of the test blocks were chosen to be the most consistent surfaces on all blocks to compare surface roughness. The top surface was not able to be measured on the MakerBotz 18s test blocks due to a solid layer of material not being applied to the top of the test blocks due to a printing error. A re-print was not possible due to the production utilizing the machine. Measuring the surface roughness of the top of the MakerBotz 18s test parts would have given results which could not be meaningfully compared with the results from the other test blocks. And the 3D Platform printer is the only printer with a heated build plate, therefore measurements were taken on the bottom and top of the 3D Platform test to allow determining the effect of the heated surface on the surface quality, and to allow the comparison of a similar surface of the other blocks.

For all measurement that were not surface roughness, dimensional measurements were taken using a Zeiss Prismo – Super Accuracy Coordinate Measuring Machine (CMM) on each test block to determine accuracy of the 3D printers. This allowed for eliminating measurement variability due to any potential human factors or human-induced errors. Measurements were taken by the CMM by touching a small measurement sphere to the surfaces of the raised and recessed shapes. Measurements were made by having the CMM trace the perimeter of each of the six shapes. The perimeters were traced in the horizontal plane at three heights above or below the main top surface of the test part. These heights were the base, middle, and top, on each raised cylinder, cone and hexagonal prism and at the base, middle and bottom for each recessed cylinder, cone and hexagonal prism. Figure 3.9 shows the location of the measurements taken on the CMM one block at a time. For each raised and recessed shape measurements were recorded for diameter, roundness and position by the CMM for each test block.

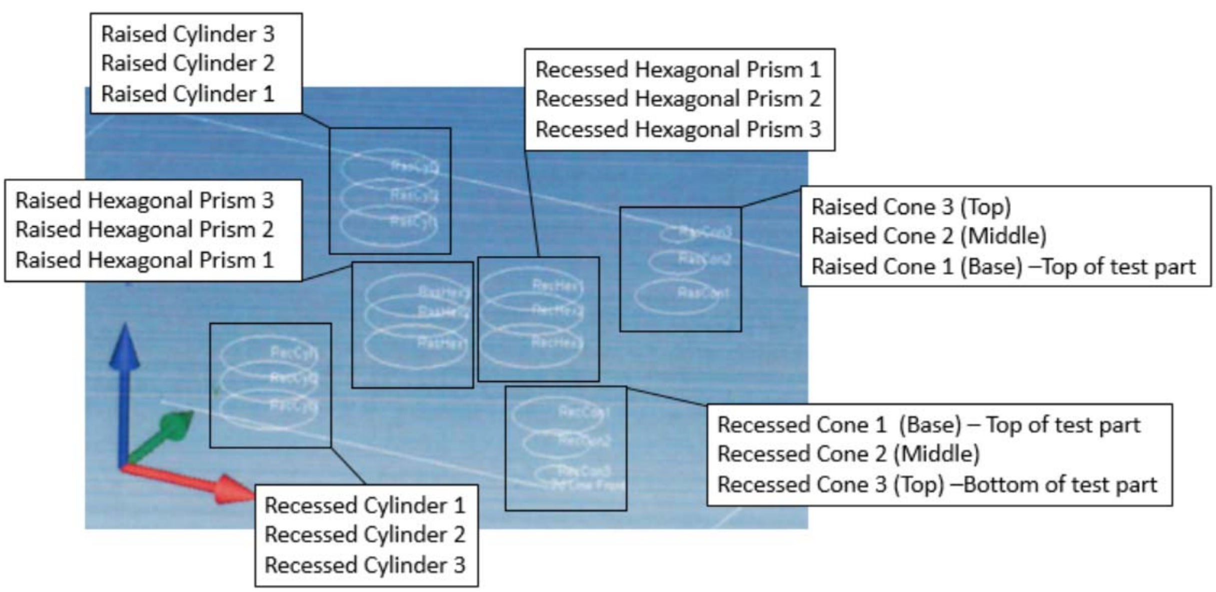

FIGURE 3. 9 CMM measurement locations on each test block feature

CHAPTER 4 RESULTS

In order to compare the three printers at the three different cost ranges, surface roughness and accuracy of geometric and dimensional features were measured and total print time was also collected to be able to compare the three printers. The results will provide the quality tradeoffs based upon the cost of the 3D printer. This will help users select a 3D printer based upon their needs.

4.1 Surface Roughness

The average surface roughness, Ra, measured for each side of the test block is shown in figure 4.1. Two measurements were taken using the MarSurf at each front side location as shown in figure 3.8.

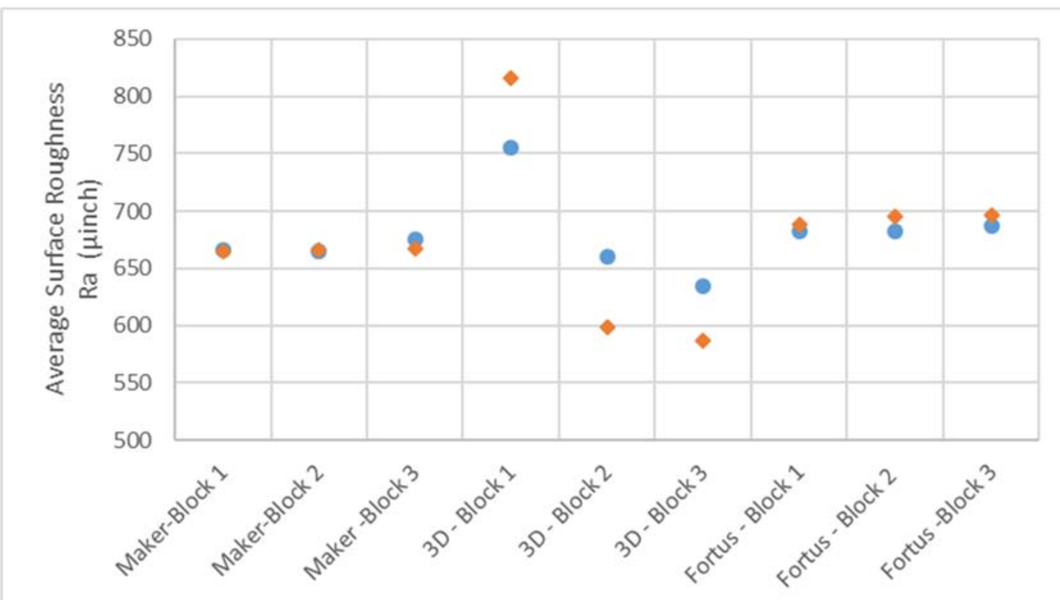

FIGURE 4. 1 Average Surface Roughness, Ra (µinch) measured on front side of test block

Average surface roughness measurements shown in figure 4.1 are consistent between the three printers except for the 3D Platform printer. Additional measurements were taken for the 3D Platform test blocks on the back side (as shown in figure 3.8) due to the inconsistency of the measurements on the front side. The 3D Platform back side measurements show to be more consistent as shown in figure 4.2. Figure 4.3 shows the gap in the filament layer on the front side of the 3D Platform block 1 resulting in inconsistent measurements in figure 4.2.

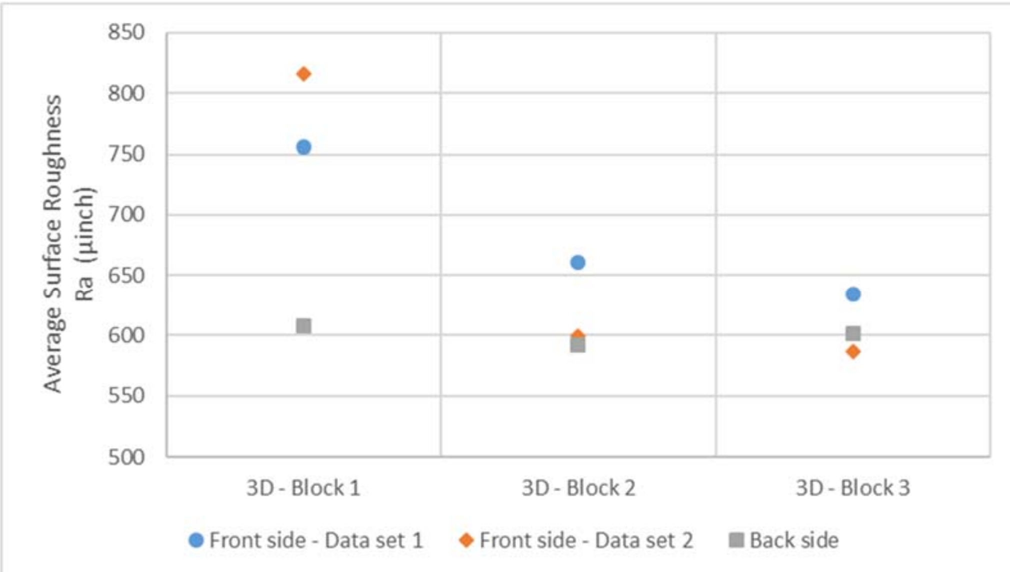

FIGURE 4. 2 Average Surface Roughness, Ra (µinch) comparison of front side and back side measurements of 3D Platform printer

FIGURE 4. 3 Gap in filament layer on front side of 3D Platform block 1

A comparison of average surface roughness measurements were also taken on the bottom of each test block perpendicular to filament bead pattern for a 1-inch travel in the center of the block with the MarSurf. MakerBotz 18s blocks were printed with a 90 degree raster angle, therefore measurements were taken on the bottom parallel to the front side as shown in figure 3.8. And measurements for both the 3D Platform and Fortus 450 were taken at a diagonal from the raised cone to the recessed cylinder, as shown in figure 3.8, since the raster angle is 45 degrees. Comparison of measurements shown in figure 4.4.

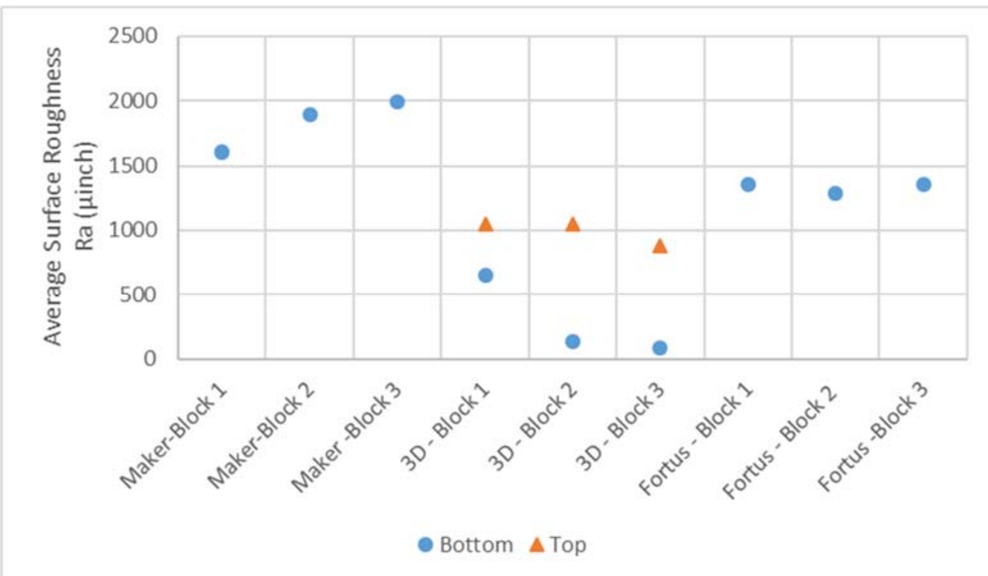

FIGURE 4. 4 Average Surface Roughness, Ra (µinch) measured on the bottom of test block. Since the 3D Platform printer has a heated build plate, while the others do not, surface roughness measurements were also measured on top of the 3D Platform test blocks to provide a better comparison to the other printer test blocks.

Average surface roughness is highest for the MakerBotz 18s, followed by the Fortus 450 and the 3D Platform printer, respectively. The 3D Platform measurements are very low compared to the two other printers as shown in figure 4.4. And of the three printers the only printer with a heated build plate is the 3D Platform printer, therefore it was determined the heated build plate may have had an effect on the surface quality. Additional measurements were taken on top of the 3D Platform test blocks for comparison as shown in figure 4.4, since the top side is not on the heated build plate.

As far as visually, there is a noticeable visual difference in the surface quality of the top and the bottom of the test blocks. Figures 4.5-4.7 show these results. Since the Fortus 450 test blocks visually appear more consistent in any direction, additional roughness measurements were also taken on the bottom perpendicular and parallel to the front side. In figure 4.4 the average surface measurement was 1354 µinch in the diagonal direction, while the measurements were 1339 µinch and 1315 µinch in the perpendicular and parallel direction, respectively. Therefore, the average surface roughness measurements were consistent even in the perpendicular and parallel direction. Also an additional measurement was taken on one of the 3D Platform test blocks that initially measured 652 µinch in figure 4.4 in the diagonal direction, but measured 487 µinch on the bottom parallel to the front side. Even though the build plate is heated the 3D Platform test block did not show consistent results with the diagonal direction measurement.

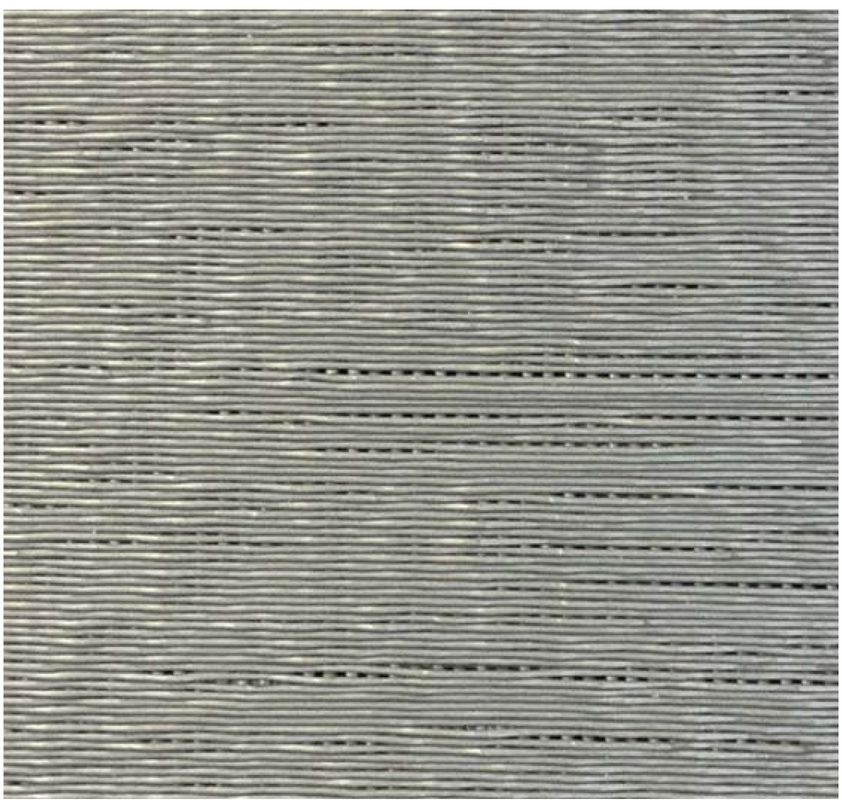

FIGURE 4. 5 Bottom of MakerBotz 18s test block showing surface quality.

FIGURE 4. 6 Bottom and Top f 3D Platform test block showing surface quality.

FIGURE 4. 7 Bottom of Fortus 450 test block showing surface quality.

4.2 Accuracy and Consistency/Repeatability

To compare the accuracy of the three printers, the following geometric and dimensional features were measured on a CMM: diameter, roundness and position of a raised and recessed cylinder, cone, and hexagonal prism.

4.2.1 Diameter measures

The diameter results for the raised cylinder are shown in figures 4.8-4.10. Measurements were taken by the CMM at the base, middle and top of each raised cylinder, cone, and hexagonal prism. And measurements were taken at the base, middle, and bottom for the recessed cylinder, cone, and hexagonal prism. Figure 4.8 shows the measurement recorded by the CMM for the raised cylinder diameter. Figure 4.9 shows the range of the diameter measurements when the base, middle and top diameter measurements are grouped together for each printer. The figure 4.9 results show the Fortus 450 has a similar range for the diameter as the 3D Platform, followed the MakerBotz 18s. Figure 4.10 shows the deviation, which is defined as the CAD diameter minus the CMM diameter measurement. In this case the CAD diameter is 0.75 inches. Again, the Fortus 450 shows to be the most accurate followed by the 3D Platform and the MakerBotz 18s, respectively.

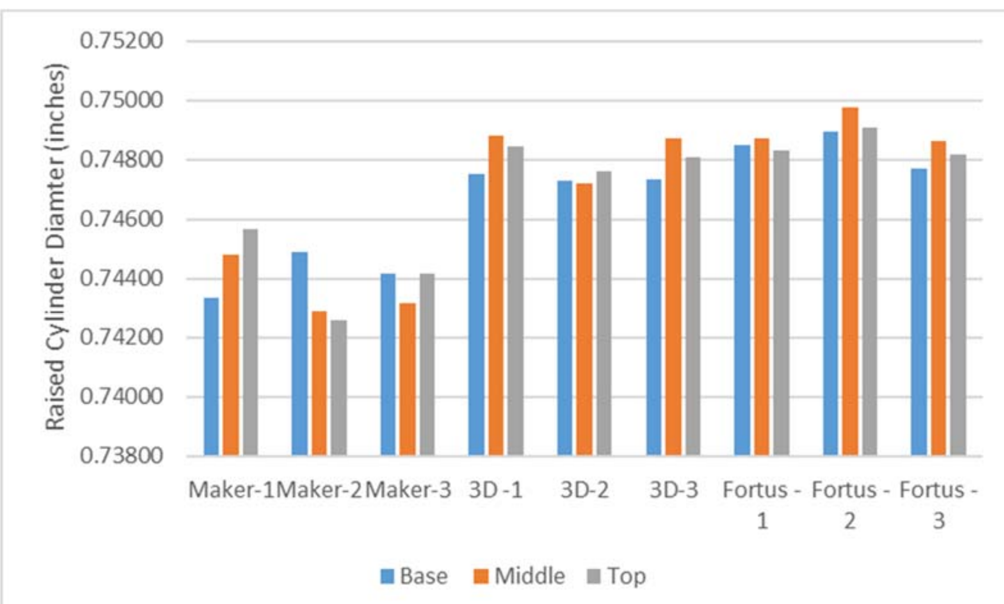

FIGURE 4. 8 Raised cylinder diameter measurements

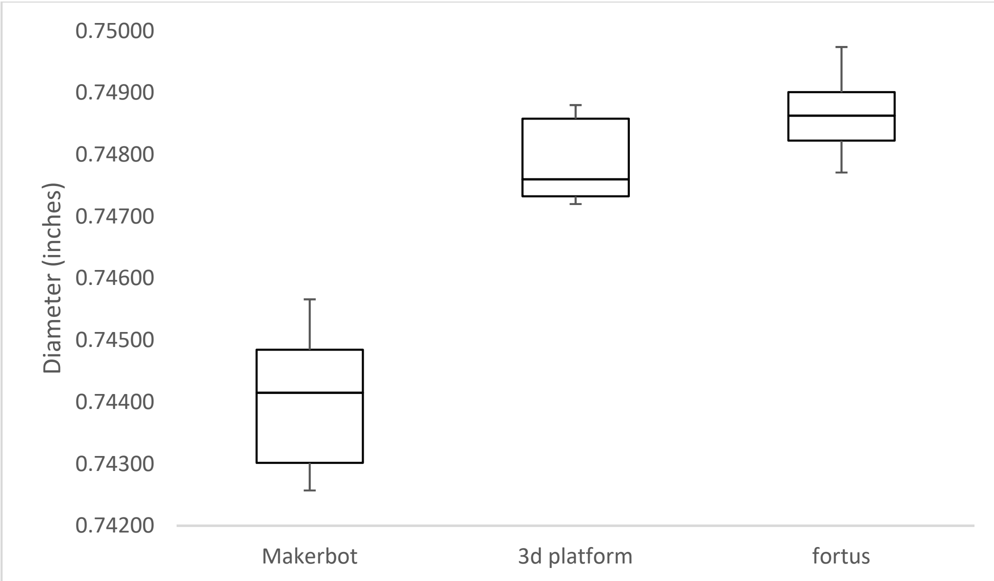

FIGURE 4. 9 Raised cylinder box and whisker plot for all base, middle and top diameter measurements grouped together for each printer

FIGURE 4. 10 Raised cylinder diameter deviation from CAD model diameter of 0.75 inches

As far as the recessed cylinder, the diameter measurements for the 3D Platform shown in figure 4.11, show a slightly better accuracy than the Fortus 450, followed by the MakerBotz

18s being the least accurate. The box and whisker plot shown in figure 4.12 shows similar results as well as the deviation from the CAD diameter shown in figure 4.13.

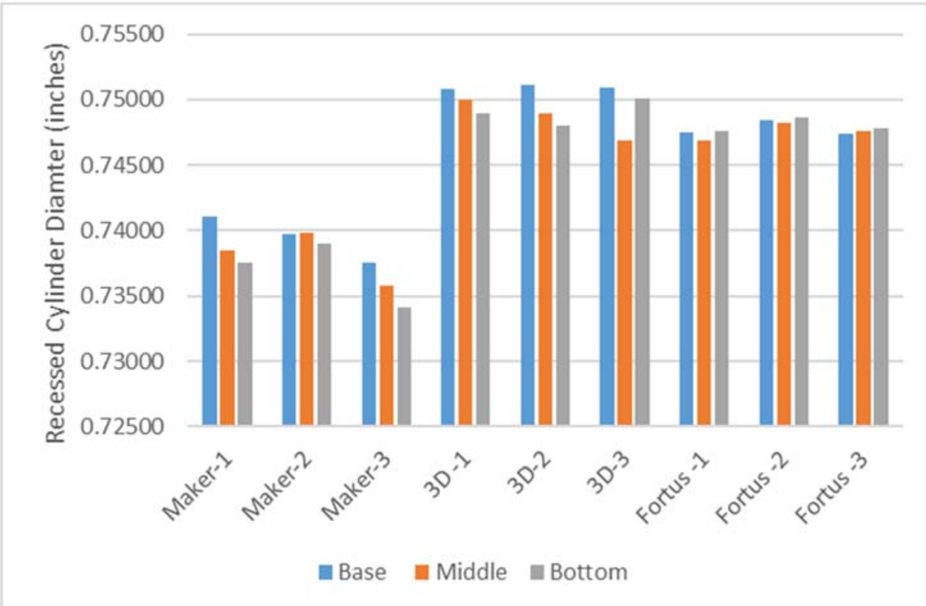

FIGURE 4. 11 Recessed cylinder diameter measurements

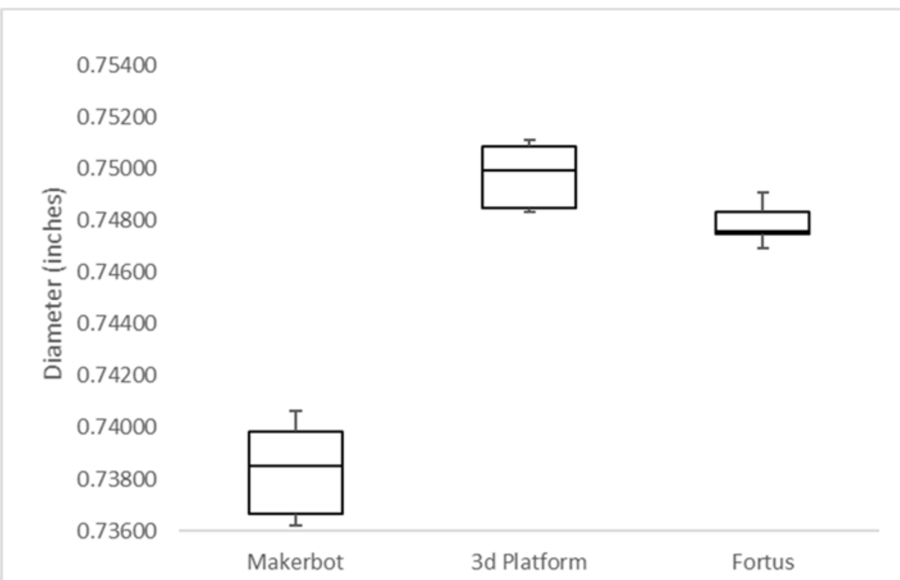

FIGURE 4. 12 Recessed cylinder box and whisker plot for all base, middle and bottom diameter measurements grouped together for each printer.

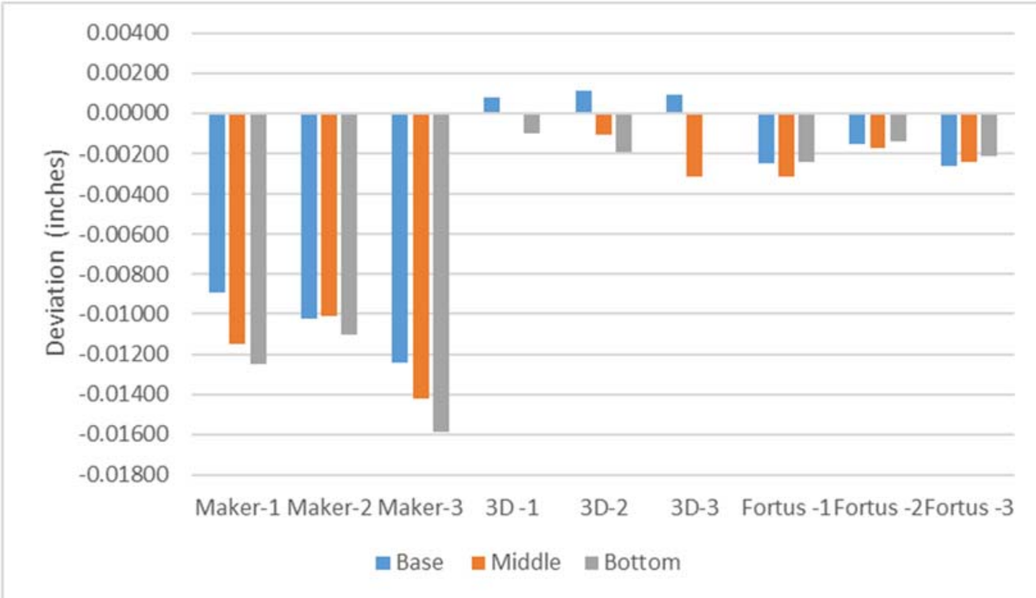

FIGURE 4. 13 Recessed cylinder diameter deviation from CAD model diameter of 0.75 inches

The following are diameter measurements recorded for the raised and recessed hexagon prism, however accuracy cannot be concluded from these measurements because a hexagonal prism is not a circular diameter. The minimum width is 0.75 inches and maximum width is 0.86 inches from the CAD model. Therefore, only consistency or repeatability can be determined from the diameter measurements recorded. For the raised hexagon prism in figure 4.14, the chart represents consistent results for the Fortus 450 between the three blocks printed on the Fortus 450 printer. The 3D Platform and MakerBotz 18s have less consistent results when comparing only the three blocks printed on the specific printer. Whereas the recessed hexagon prism diameter measurements show slightly more consistency when comparing the three test blocks printed for each specific printer as shown in figure 4.16.

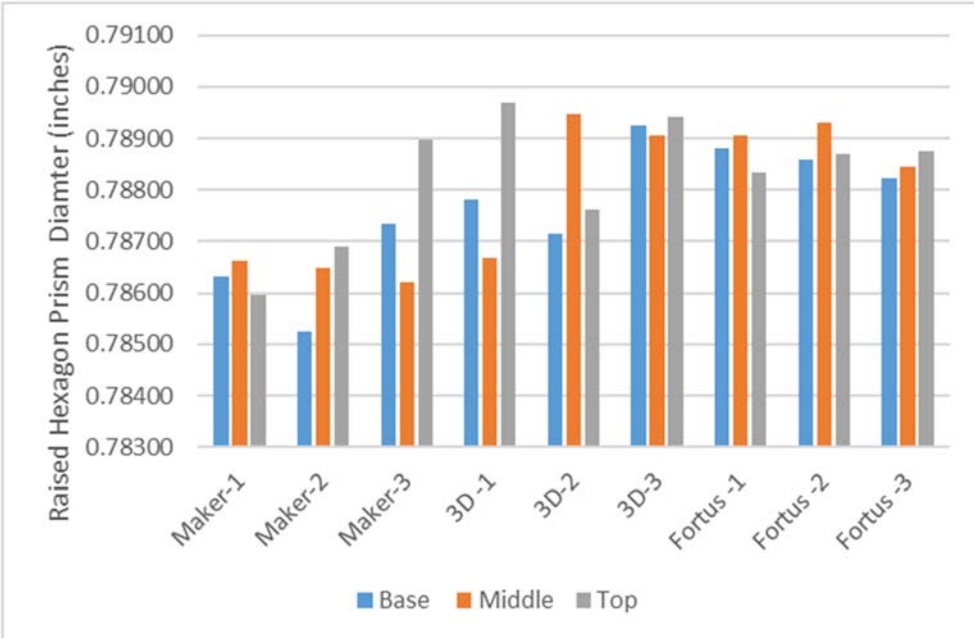

FIGURE 4. 14 Raised hexagonal prism diameter measurements

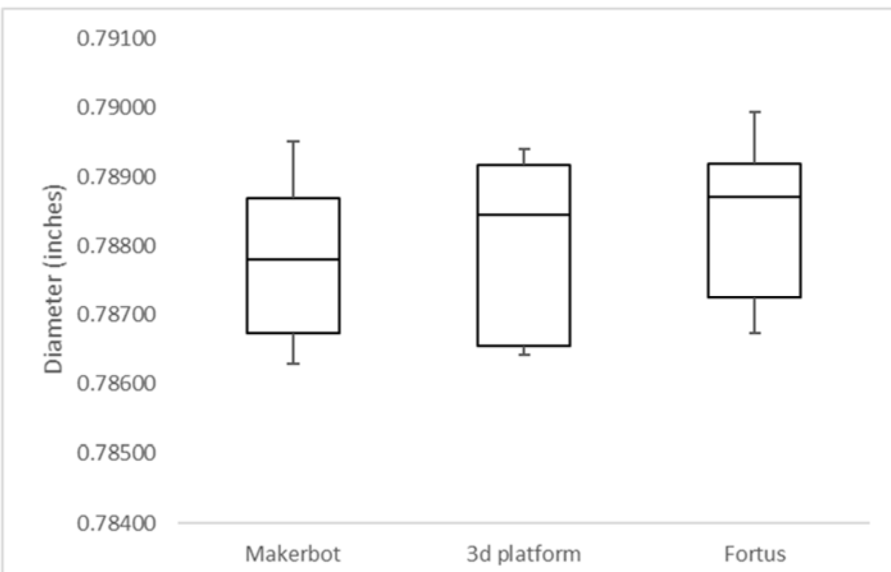

FIGURE 4. 15 Raised hexagonal prism box and whisker plot for all base, middle and bottom diameter measurements grouped together for each printer.

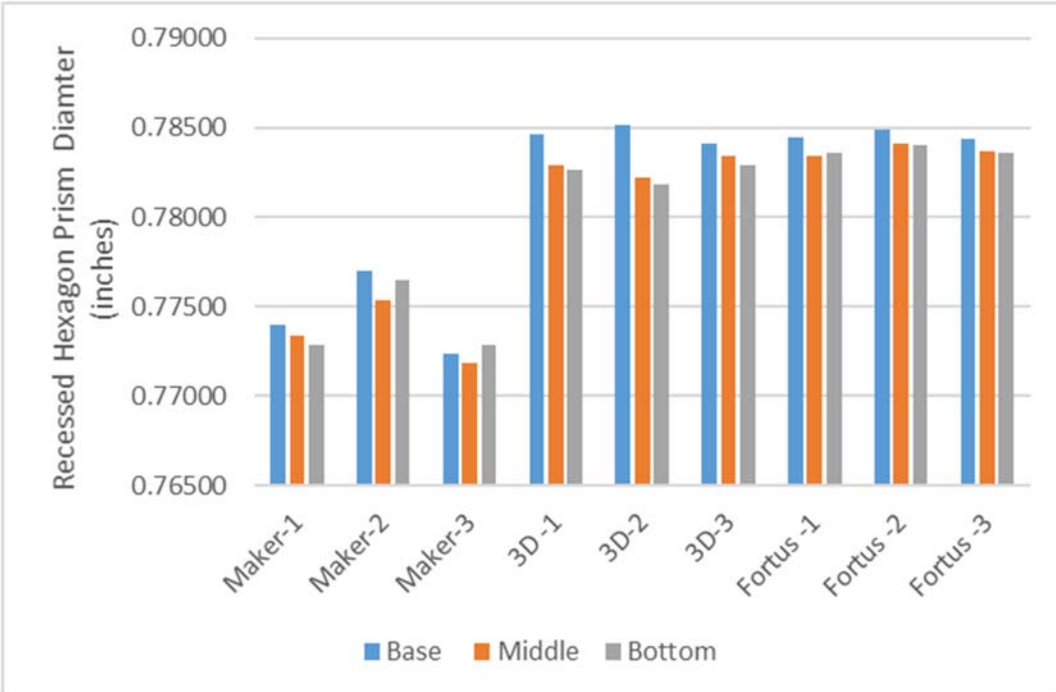

FIGURE 4. 16 Recessed hexagonal prism diameter measurement

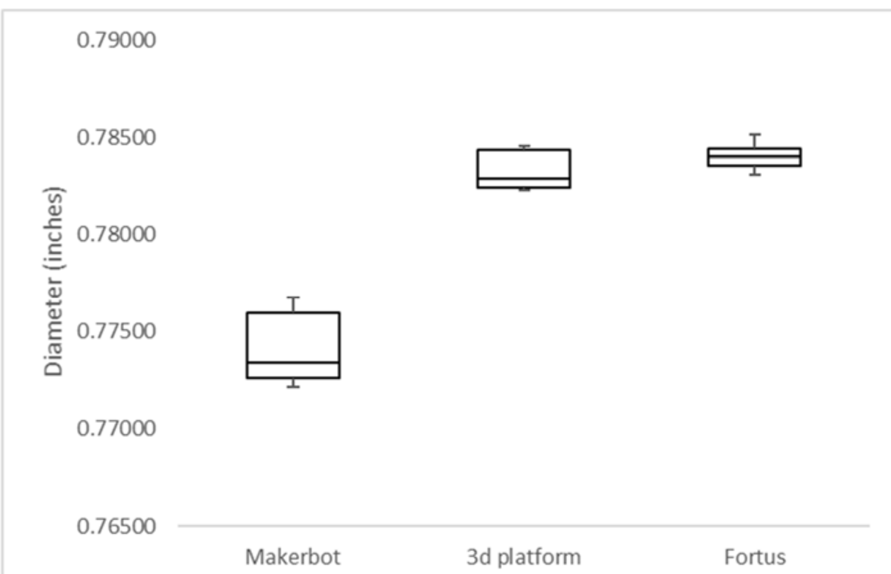

FIGURE 4. 17 Recessed hexagonal prism box and whisker plot for all base, middle and bottom diameter measurements grouped together for each printer.

The diameter measurement results for the raised and recessed cone are shown in figures 4.18-4.21. All three printers for the raised and recessed cone show consistent results, therefore no specific printer shows better a result from one printer to the other. In figures 4.19 and 4.21, deviation for the both the raised and recessed cone show similar results as far as consistency however the deviations are quite large based upon the CAD model of a base diameter of 0.75 inches, a middle diameter of 0.275 inches calculated mid-point based upon similar triangles and a top/bottom diameter of 0.20 inches. The large deviations are a result of the CMM probe recording measurements not exactly where the CAD measurements are defined. Therefore, accuracy cannot be determined and only consistency/repeatability can be reviewed for the raised and recessed cone.

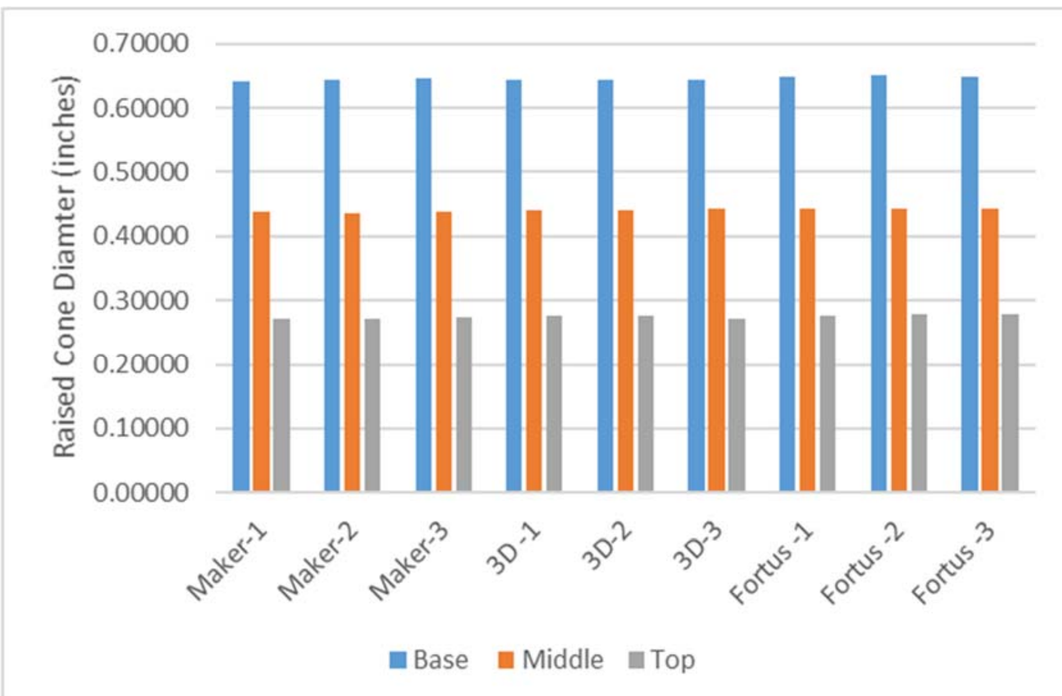

FIGURE 4. 18 Raised cone diameter measurements

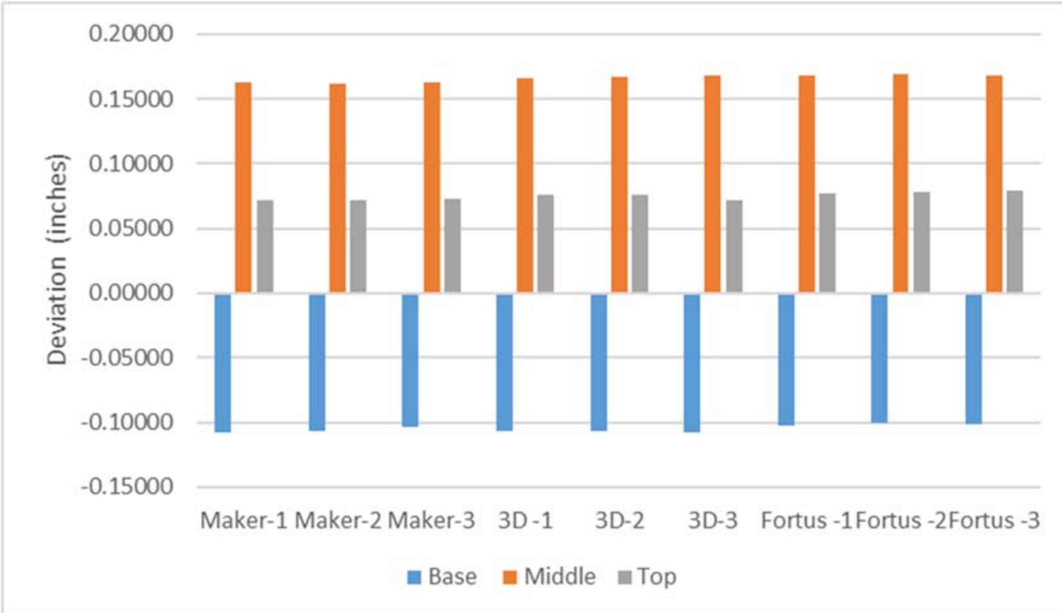

FIGURE 4. 19 Raised cone diameter deviation from CAD model top diameter of 0.20 inches, middle diameter of 0.275 inches, and base diameter of 0.75 inches.

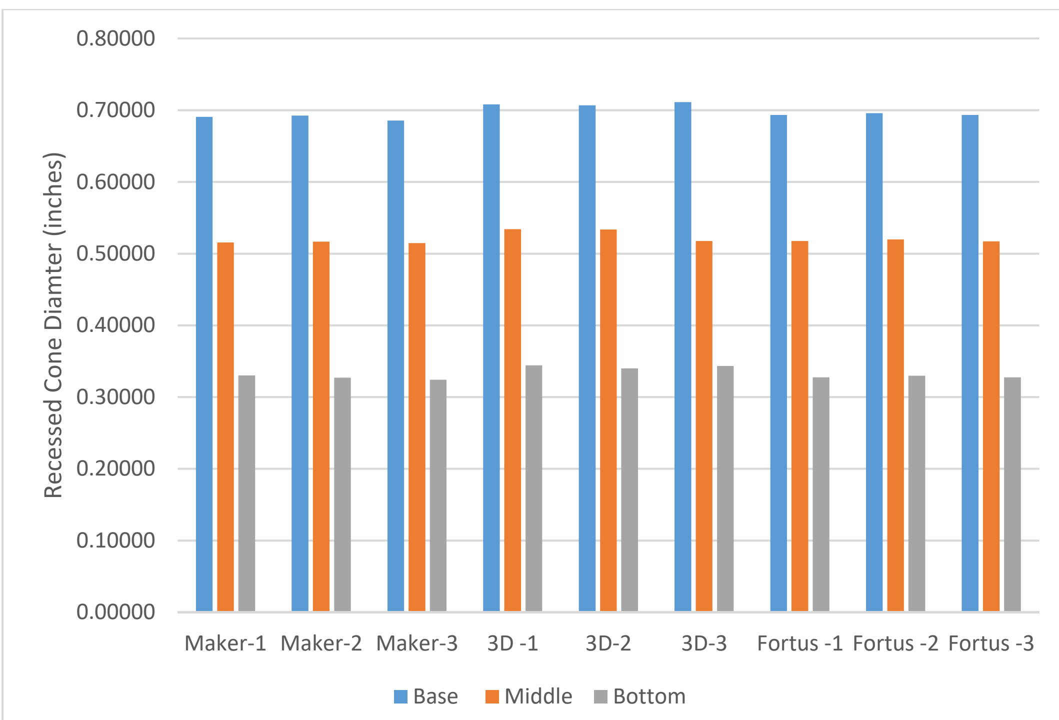

FIGURE 4. 20 Recessed cone diameter measurements

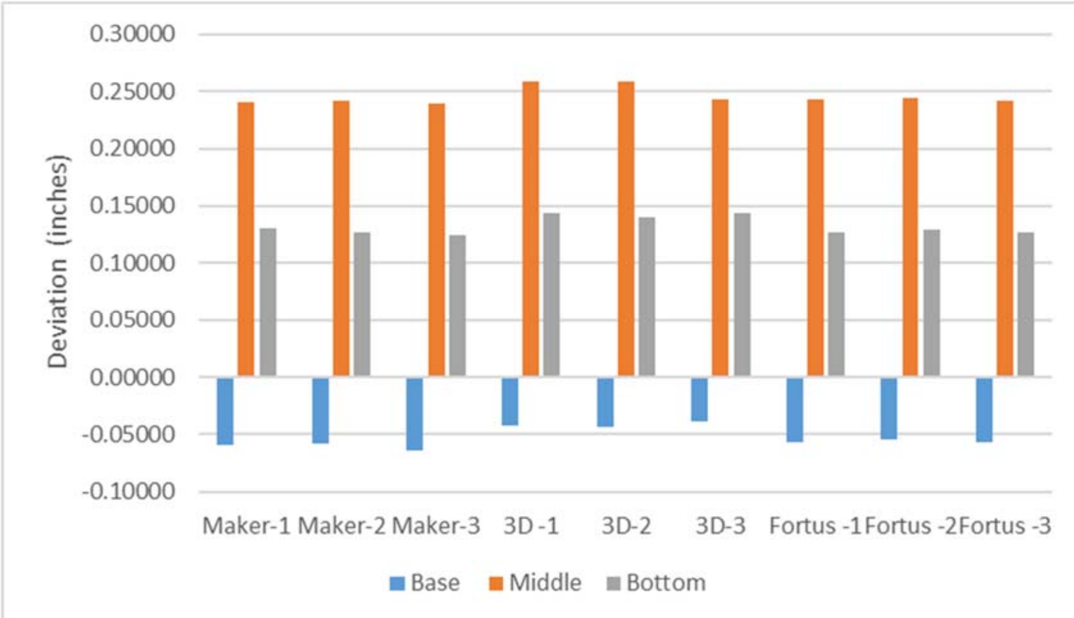

FIGURE 4. 21 Recessed cone deviation diameter from CAD model bottom diameter of 0.20 inches, middle diameter of 0.275 inches, and base diameter of 0.75 inches.

Based on the review above, a summary of the results of the three 3D printers for diameter for the raised and recessed cylinder, cone and hexagonal prism are shown in table 4.1. Each printer was ranked based upon, first, accuracy of the diameter measurement versus the CAD model diameter if accuracy was a reasonable measurement for the feature, then based upon, consistency or repeatability. For consistency, test blocks were compared to test blocks printed by the same printer. The closer the measurements are to one another for the specific printer, the more consistent the printer. The various performance metrics for the printers were ranked with the best performer being given a 3 and the worst being given a 1. If any printers were close in accuracy or consistency then both or all printers received the same rating. The overall rank closest to 3 had the best performance and the rank closest to 1 is the worst performance.

TABLE 4. 1 Printer rank of diameter measurements for accuracy and consistency/repeatability.

	3D PRINTER		
DIAMETER - Accuracy Rank	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Raised Cylinder	1	2	3
Recessed Cylinder	1	3	2
Raised Hexagonal Prism	N/A	N/A	N/A
Recessed Hexagonal Prism	N/A	N/A	N/A
Raised Cone	N/A	N/A	N/A
Recessed Cone	N/A	N/A	N/A
DIAMETER AVERAGE RANK - Accuracy	1	2.5	2.5
DIAMETER - Consistency/Repeatability Rank	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Raised Cylinder	1	3	3
Recessed Cylinder	2	2	3
Raised Hexagonal Prism	2	1	3
Recessed Hexagonal Prism	1	2	3
Raised Cone	2	2	2
Recessed Cone	2	2	2
DIAMETER AVERAGE RANK - Consistency	1.67	2	2.67

4.2.2 Position error measurements

The position error measurements for the raised cylinder are shown in figures 4.22 and 4.23. In figure 4.22, the Fortus 450 is the closest to zero meaning it is the most accurate, followed by the MakerBotz 18s and the 3D Platform printer,respectively. However, as far as consistency the Fortus 450 is best across the base, middle and top position measurement for individual Fortus 450 test blocks.

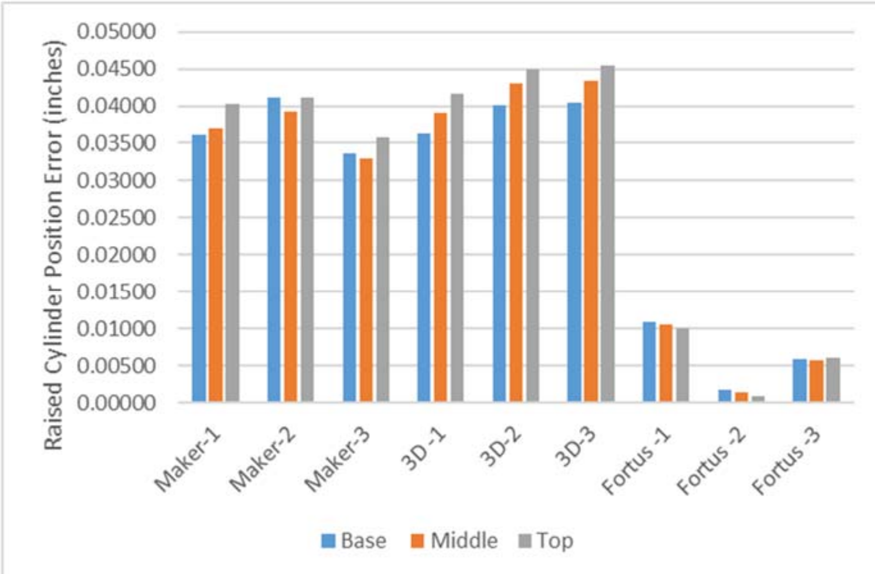

FIGURE 4. 22 Raised Cylinder position error measurements

In figure 4.23, the box and whisker plot shows the range of the position error measurements by grouping all the base, middle and top position measurements for each printer. The position measurements are closest in range for the 3D Platform but have a larger error. The range is similar for the MakerBotz 18s, then followed by the Fortus 450, but the Fortus 450 is closest to zero, meaning the position of the feature is closest to the CAD drawing position.

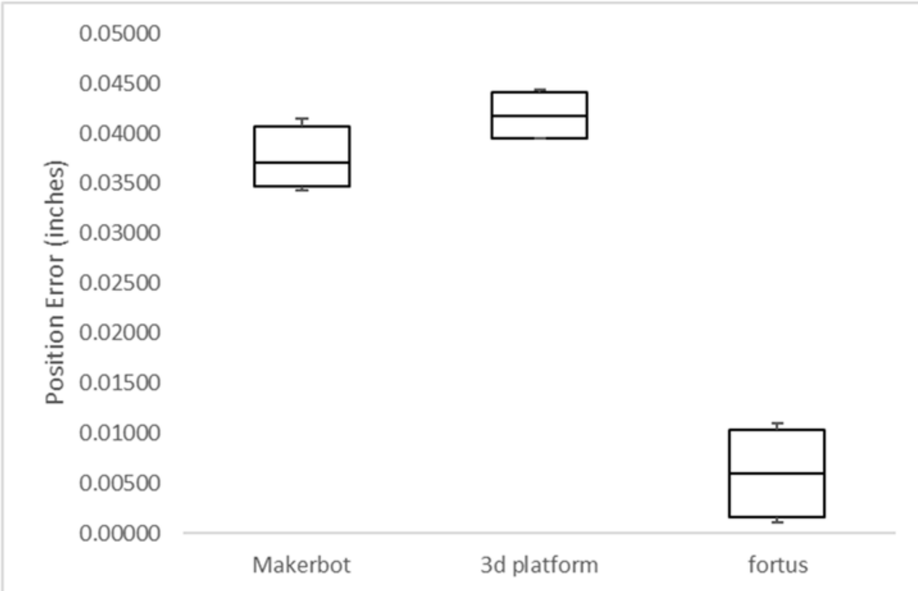

FIGURE 4. 23 Raised cylinder box and whisker plot for all base, middle and top position error measurements grouped together for each printer

The position error results for the recessed cylinder are shown in figures 4.24 and 4.25. The Fortus 450 is most consistent and has the least amount of error. The 3D Platform printer has a consistent increase in position error in the direction of increased layer height (z-direction) for the 3D Platform printer. Overall, the error is quite large for the MakerBotz 18s and for the 3D Platform printer error measurements at the base. In figure 4.25, the box and whisker plot show the range the position error when all the base, middle and bottom measurements are grouped together for each printer. As expected the 3D Platform has the largest range due to the increase in error in the z-direction. The Fortus 450 and the MakerBotz 18s are fairly similar however the error is much larger for the MakerBotz 18s.

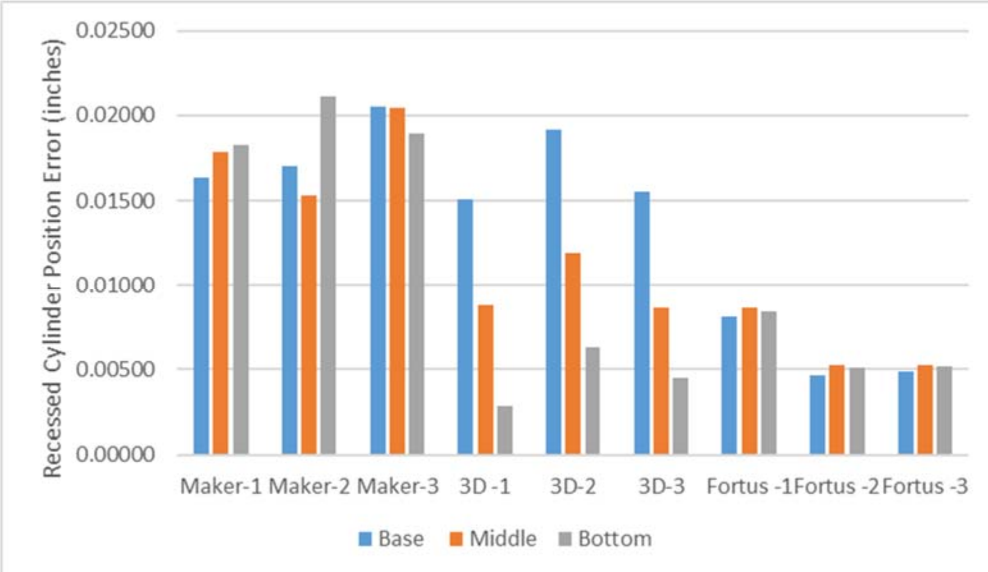

FIGURE 4. 24 Recessed cylinder position error measurements

FIGURE 4. 25 Recessed cylinder box and whisker plot for all base, middle and bottom position error measurements grouped together for each printer

The raised and recessed hexagonal prism position error results are shown in figures 4.26-4.29. The trend for positon error for the raised hexagonal prism is largest for the MakeBotz 18s, followed by the 3D Platform and the Fortus 450, respectively. In figure 4.27, the box and whisker plot of the raised hexagonal position error, the range is smallest for the Fortus 450, followed by the 3D Platform and MakerBotz 18s, respectively.

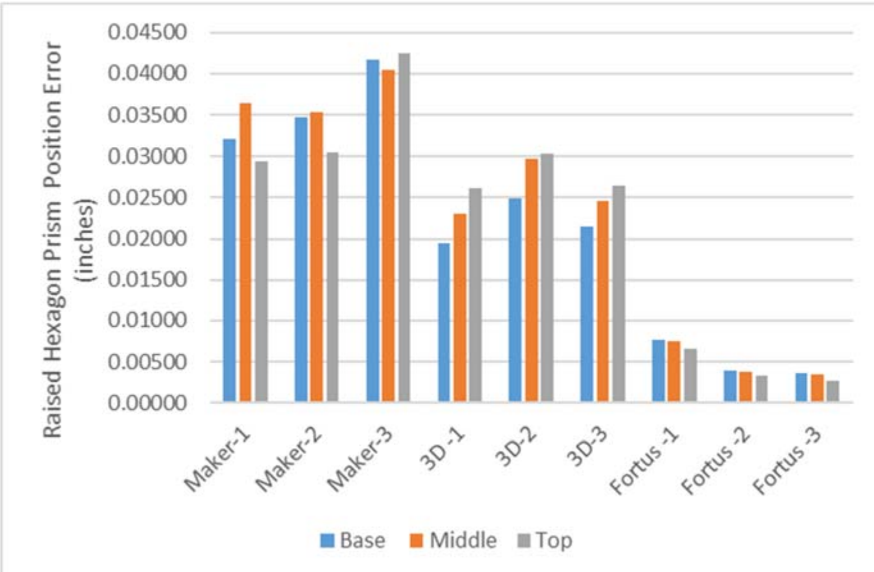

FIGURE 4. 26 Raised hexagonal prism position measurements

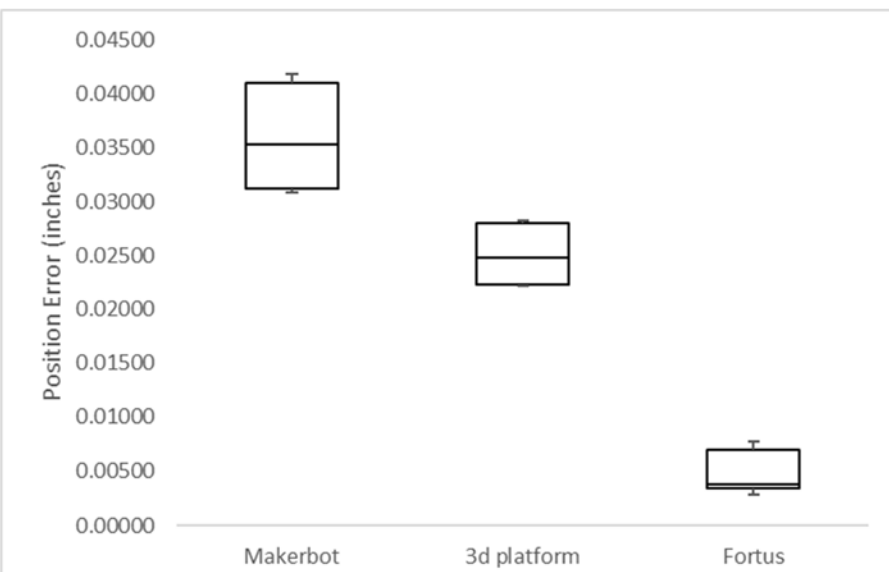

FIGURE 4. 27 Raised hexagonal prism box and whisker plot for all base, middle and top position error measurements grouped together for each printer

The trend for the recessed hexagonal prism position error is similar to the raised hexagonal prism. As shown in figure 4.28, the Fortus 450 has the least amount of error followed by the 3D Platform and MakerBotz 18s printer, respectively. The box and whisker plot in figure 4.29 shows all three printers have similar consistency.

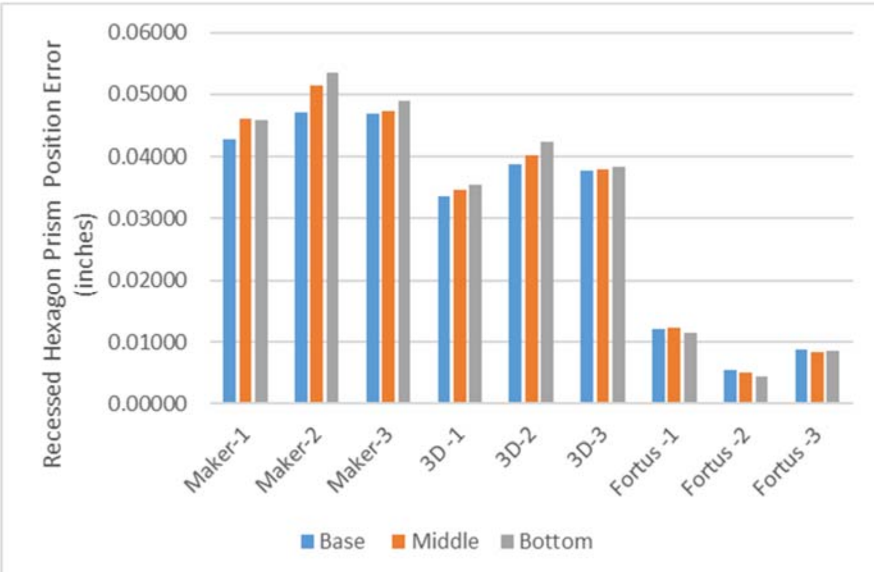

FIGURE 4. 28 Recessed hexagonal prism position error measurements

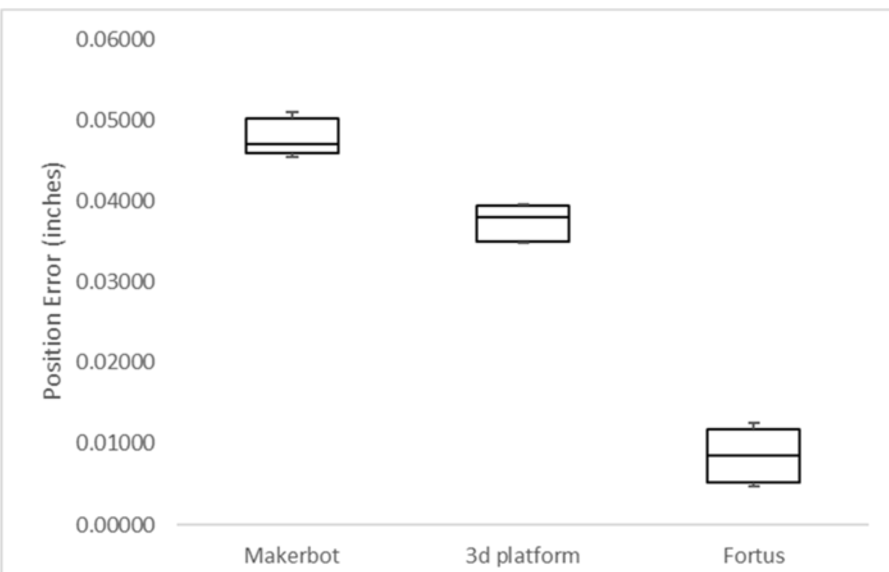

FIGURE 4. 29 Recessed hexagonal prism box and whisker plot for all base, middle and bottom position measurements grouped together for each printer

The position error results for the raised and recessed cone are shown in figures 4.30-4.33. The Fortus 450 position error is the most accurate, followed by 3D Platform and the MakerBotz 18s, respectively. As far as the range of error, shown in figure 4.31, as with the recessed hexagonal prism all three printers similar in consistency.

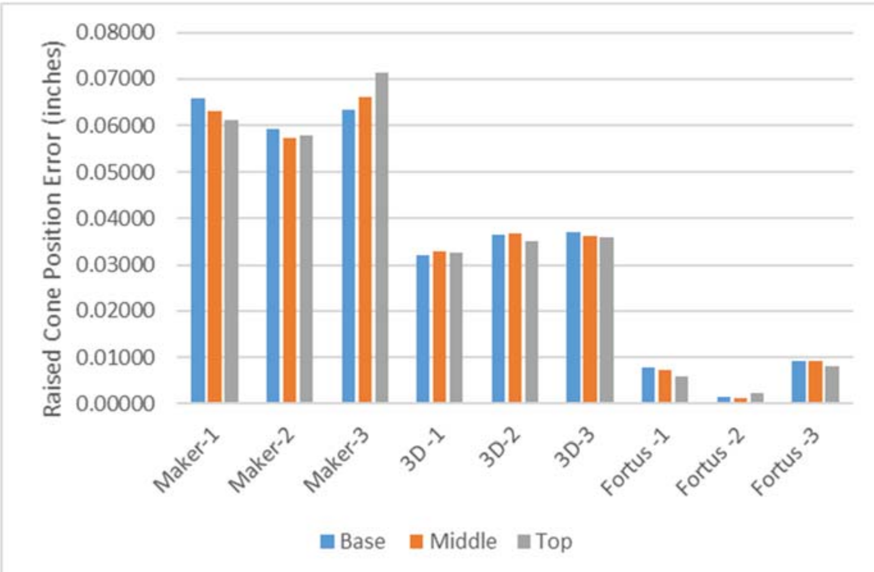

FIGURE 4. 30 Raised cone position error measurements

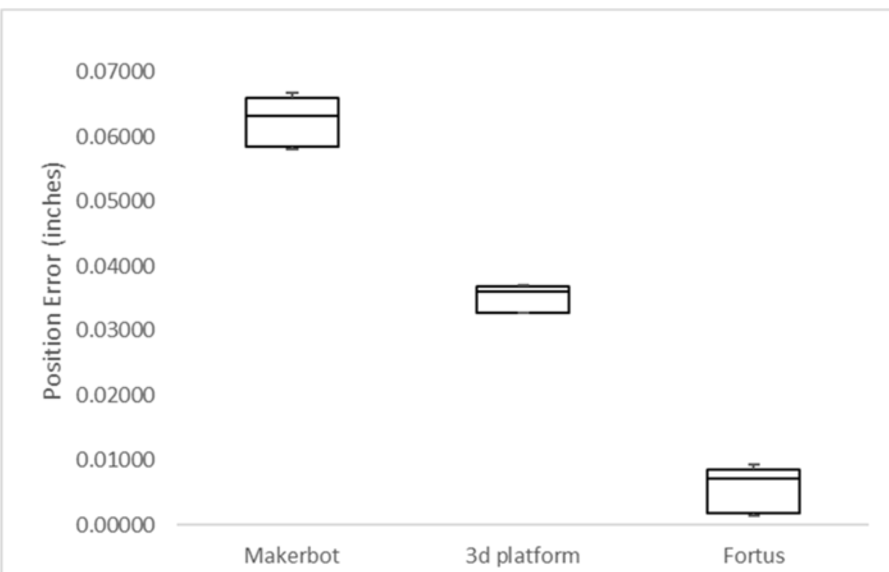

FIGURE 4. 31 Raised cone position and whisker plot for all base, middle and top position error measurements grouped together for each printer

In figure 4.32 the position error for the recessed cone is similar to the raised cone, with error being the smallest for the Fortus 450. The 3D Platform shows a slight decrease in error as the layer height increases. The MakerBotz 18s also has the largest error overall. The range shown in figure 4.33 shows the Fortus 450 has the closest range of error, followed by the 3D Platform and MakerBotz 18s, respectively.

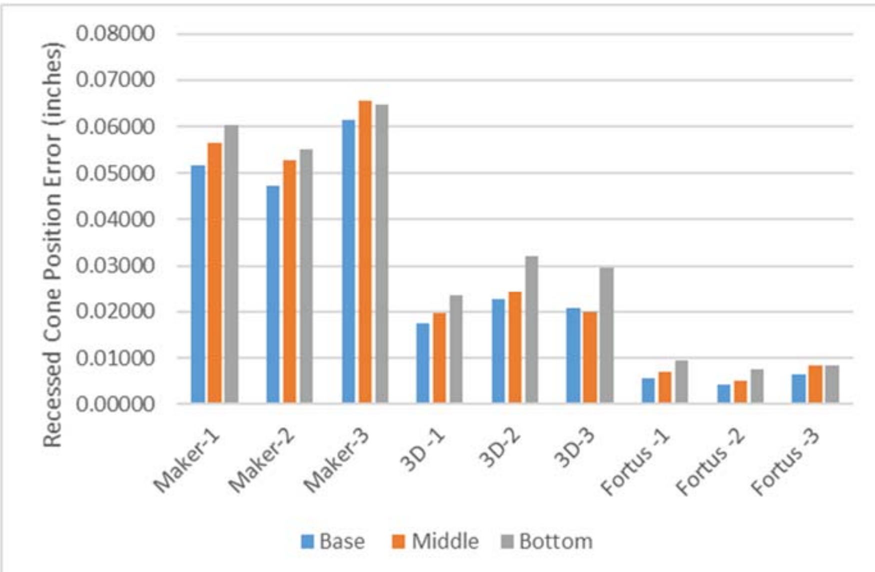

FIGURE 4. 32 Recessed cone position error measurements

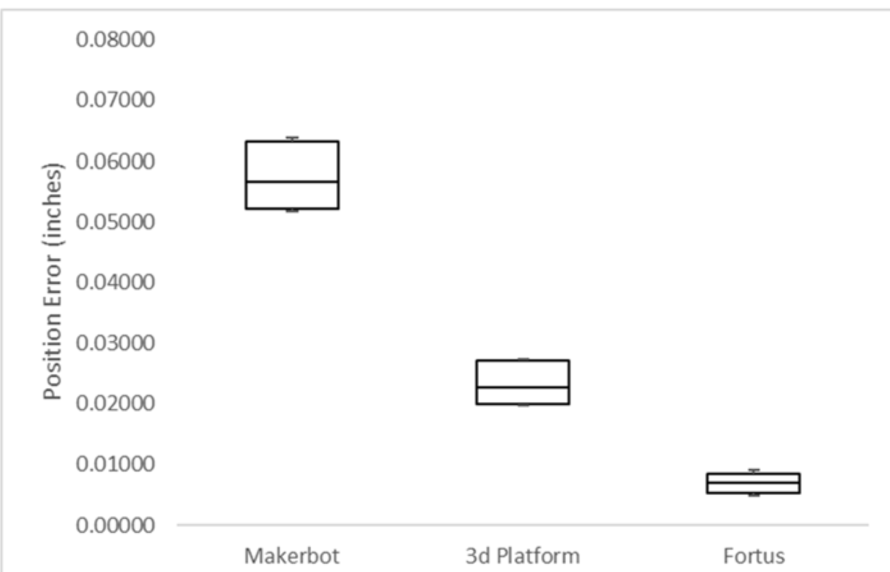

FIGURE 4. 33 Recessed cone box and whisker plot for all base, middle and bottom position error measurements grouped together for each printer

Table 4.2 summarizes printer rank for the raised and recessed cylinder, cone and hexagonal prism. The position error measurements were ranked as the diameter measurements were ranked. Position error measurements were ranked by accuracy, the best accuracy meaning the position of the feature is closest to the CAD model position. And also ranked based upon, consistency or repeatability. For consistency, test blocks were only compared to test blocks printed by the same printer. The closer the measurements are to one another for the specific printer, the more consistent the printer. The various performance metrics for the printers were ranked with the best performer being given a 3 and the worst being given a 1. If any printers were close in accuracy or consistency then both or all printers received the same rating. The overall rank closest to 3 had the best performance and the rank closest to 1 is the worst performance.

TABLE 4. 2 Printer rank of position error for accuracy and consistency/repeatability

	3D PRINTER		
POSITION ERROR - Accuracy	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Raised Cylinder	2	2	3
Recessed Cylinder	1	2	3
Raised Hexagonal Prism	1	2	3
Recessed Hexagonal Prism	1	2	3
Raised Cone	3	3	3
Recessed Cone	1	2	3
POSITION ERROR AVERAGE RATING - Accuracy	1.50	2.17	3.00

POSITION ERROR - Consistency/Repeatability	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Raised Cylinder	2	2	3
Recessed Cylinder	2	1	3
Raised Hexagonal Prism	1	2	3
Recessed Hexagonal Prism	3	3	3
Raised Cone	1	3	2
Recessed Cone	1	2	3
POSITION ERROR AVERAGE RATING - Consistency	1.67	2.17	2.83

4.2.3 Roundness measurements

The roundness measurement results for the raised cylinder are shown in figures 4.34 and 4.35. In figure 4.34, the Fortus 450 is the closest to zero meaning it is the most accurate, followed by the 3D Platform and MakerBotz 18s, respectively. And as far as consistency, the Fortus 450 and the 3D Platform are similar, while the MakerBotz 18s has some outlying measurements, similarly to what is shown in figure 4.35 of the box and whisker plot.

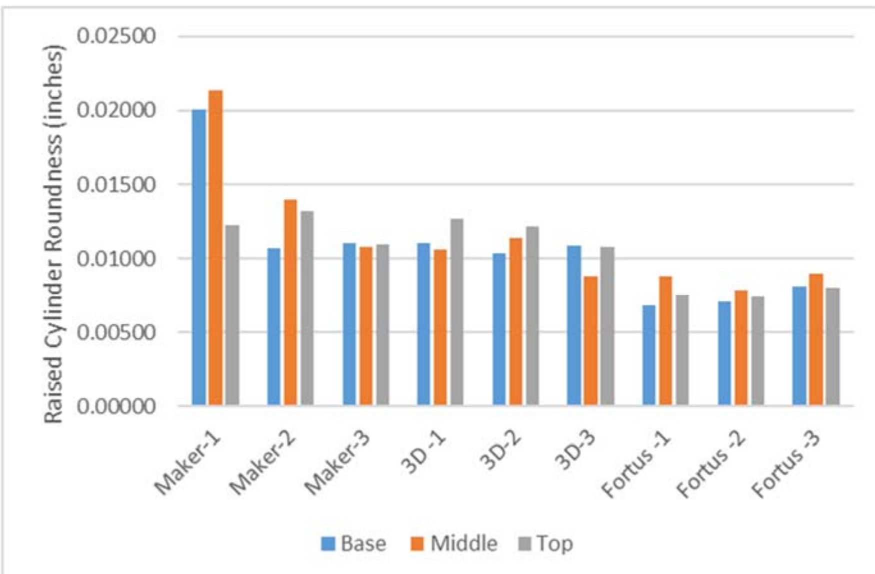

FIGURE 4. 34 Raised cylinder roundness measurements. The closer to zero the more accurate the measurement.

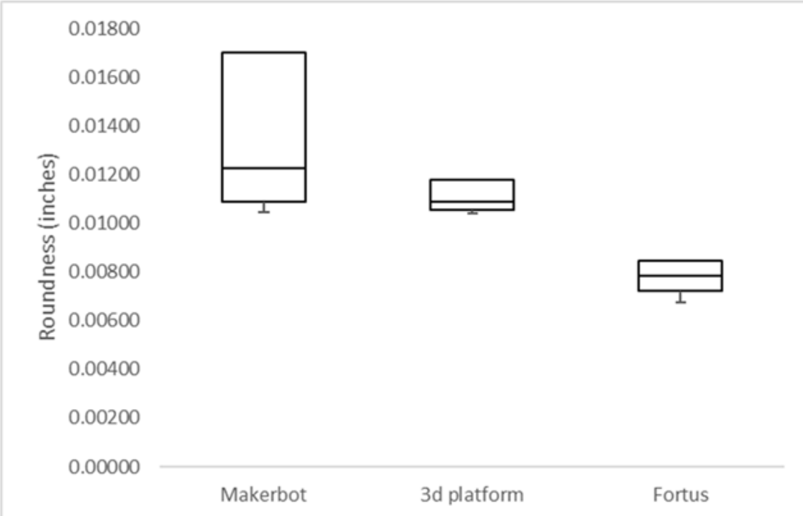

FIGURE 4. 35 Raised cylinder box and whisker plot for all base, middle and top roundness measurements group together for each printer.

For the recessed cylinder the roundness measurements are shown in figures 4.36 and 4.37. The Fortus 450 is the most consistent and slightly more accurate than the MakerBotz 18s. The 3D Platform is the least accurate, but consistent except for one outlying measurement.

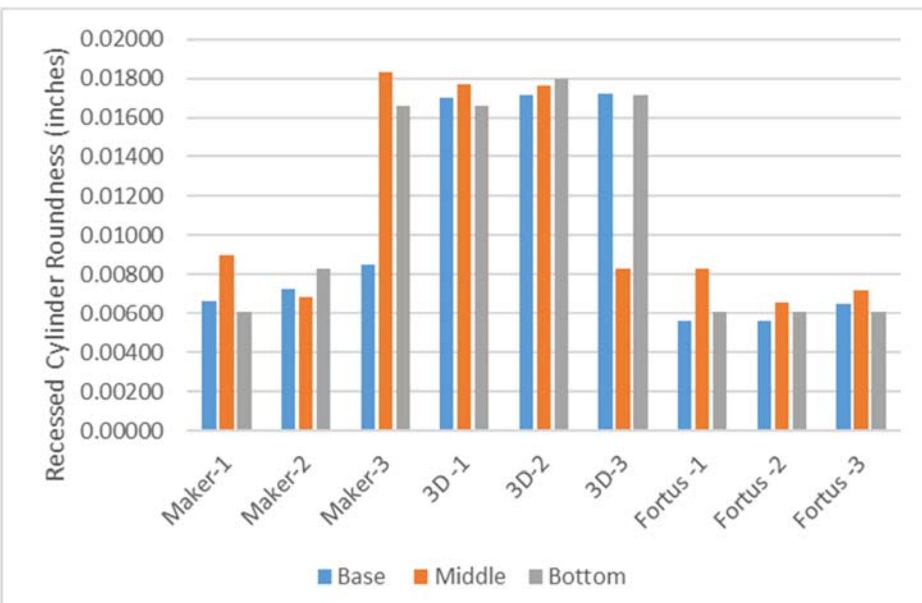

FIGURE 4. 36 Recessed cylinder roundness measurements. The closer to zero the more accurate the measurement.

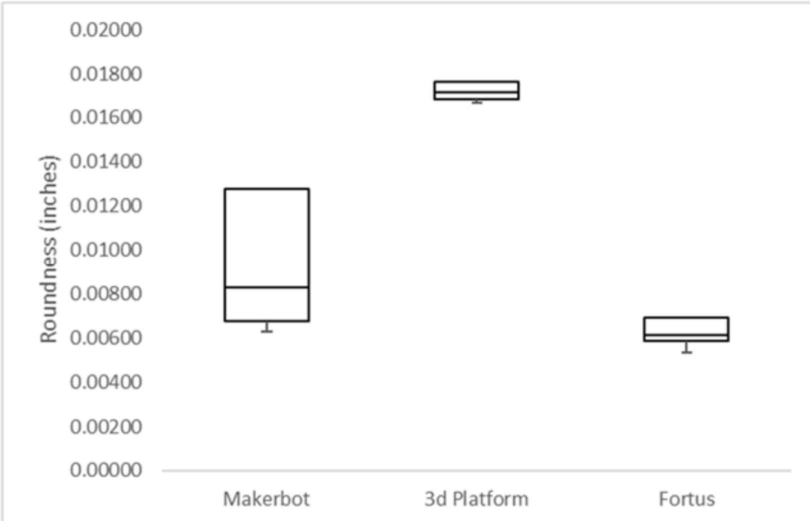

FIGURE 4. 37 Recessed cylinder box and whisker plot for all base, middle and bottom roundness measurements for each printer.

The raised and recessed hexagonal prism roundness measurements are shown in figures 4.38-4.41. As mentioned previously the hexagonal prism is not a true circular diameter, therefore, only consistency is the only reasonable analysis of the roundness measurements. For the raised hexagonal prism, the Fortus 450 is slightly more consistent than the 3D Platform, then followed by the MakerBotz 18s which has a few outlying measurements. For the recessed hexagonal prism, as shown in figure 4.41, the recessed hexagonal prism box and whisker plot, the Fortus 450 has the smallest range of measurements, therefore is the most consistent of the three printers. The 3D Platform and MakerBotz 18s are very similar in consistency.

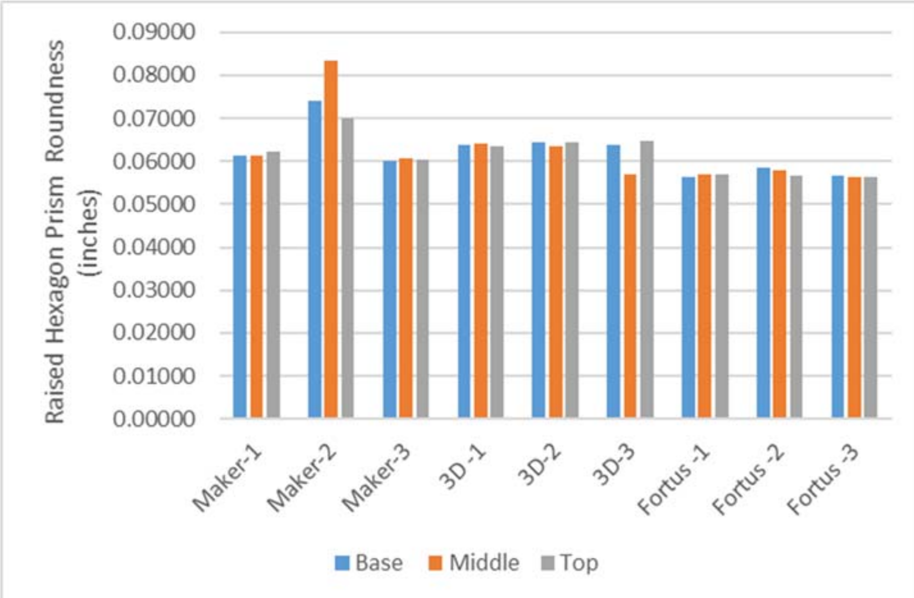

FIGURE 4. 38 Raised hexagonal prism roundness measurements. The closer to zero the more accurate the measurement.

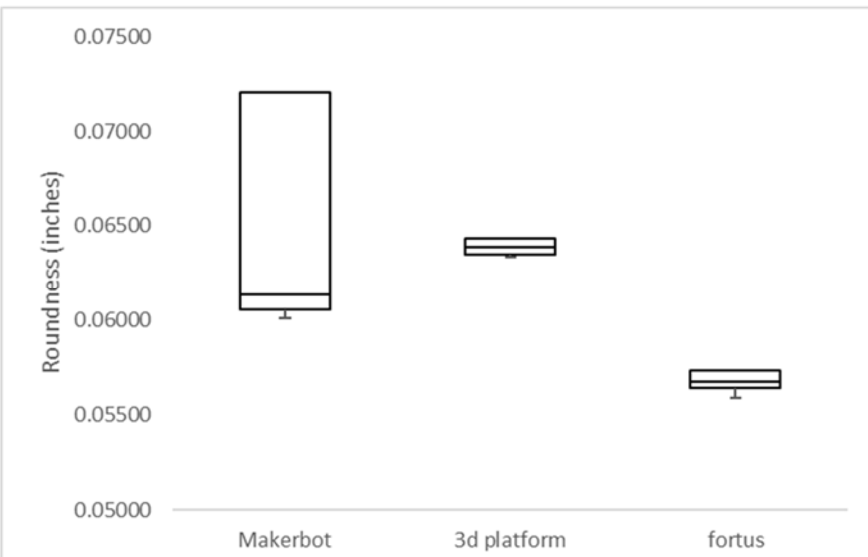

FIGURE 4. 39 Raised hexagonal prism box and whisker plot for all base, middle and top roundness measurements grouped together for each printer.

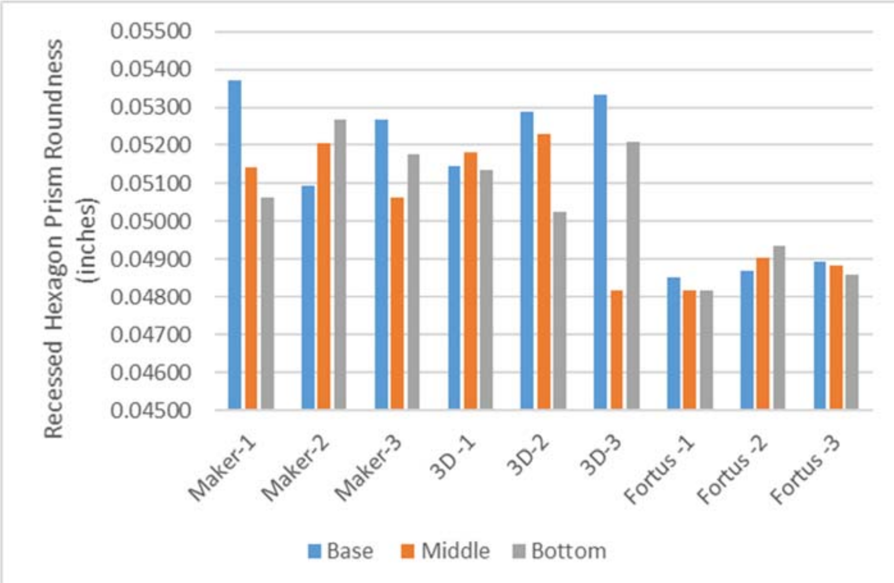

FIGURE 4. 40 Recessed hexagonal prism roundness measurements. The closer to zero the more accurate the measurement.

FIGURE 4. 41 Recessed hexagonal prism box and whisker plot for all base, middle and bottom roundness measurements grouped together for each printer.

The raised and recessed cone roundness measurement results are shown in figures 4.42—4.45. For the raised cone roundness, the Fortus 450 is the most accurate, followed by the 3D Platform and the MakerBotz 18s, respectively. For consistency, the Fortus 450 and the 3D Platform are similar and the MakerBotz 18s is the least consistent, as shown in figure 4.43. For the recessed cone roundness measurements, the MakerBotz 18s is more accurate in figure

4.44, followed by the Fortus 450 and the 3D Platform, respectively. However, in figure 4.45, the 3D Platform shows to be more consistent with a smaller range of roundness measurements, followed by the MakerBotz 18s and the Fortus 450, respectively.

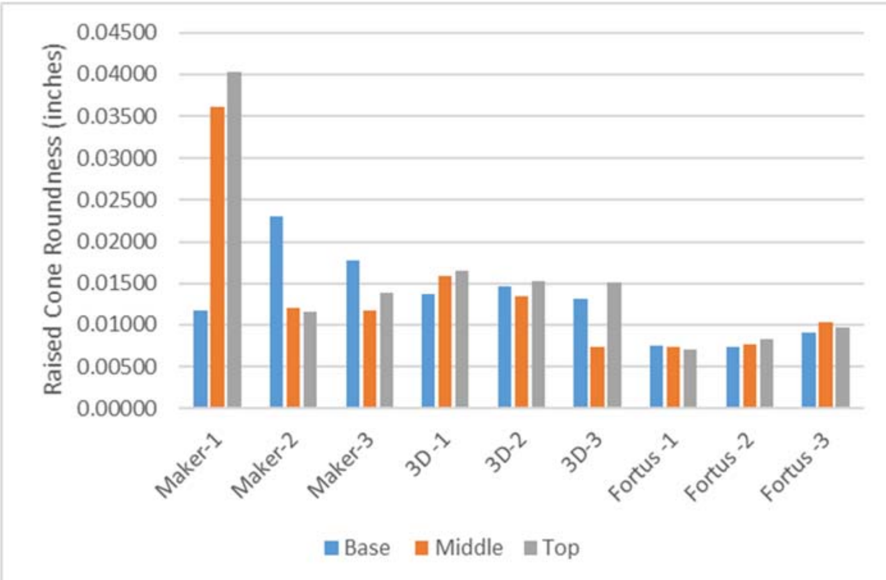

FIGURE 4. 42 Raised cone roundness measurements. The closer to zero the more accurate the measurement.

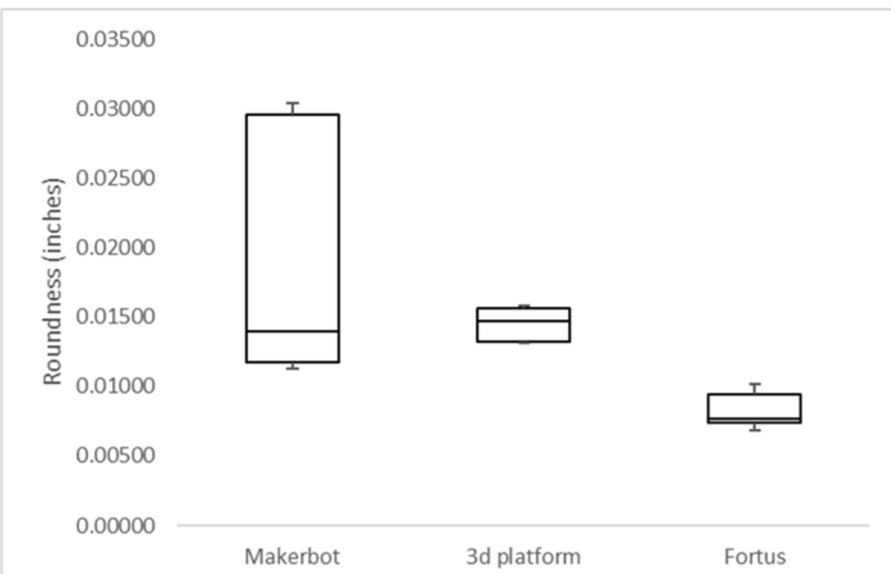

FIGURE 4. 43 Raised cone box and whisker plot for all base, middle and top roundness measurements grouped together for each printer

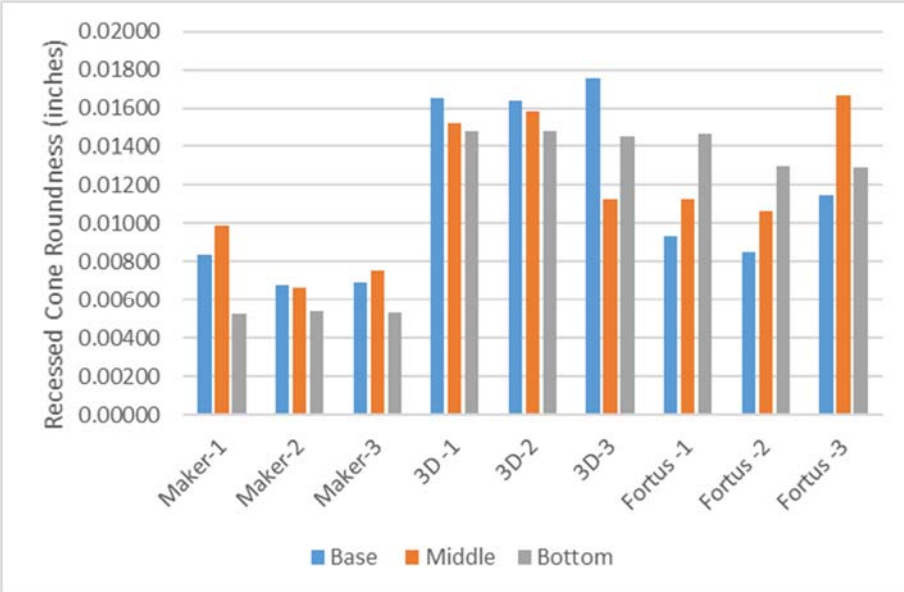

FIGURE 4. 44 Recessed cone roundness measurements. The closer to zero the more accurate the measurement.

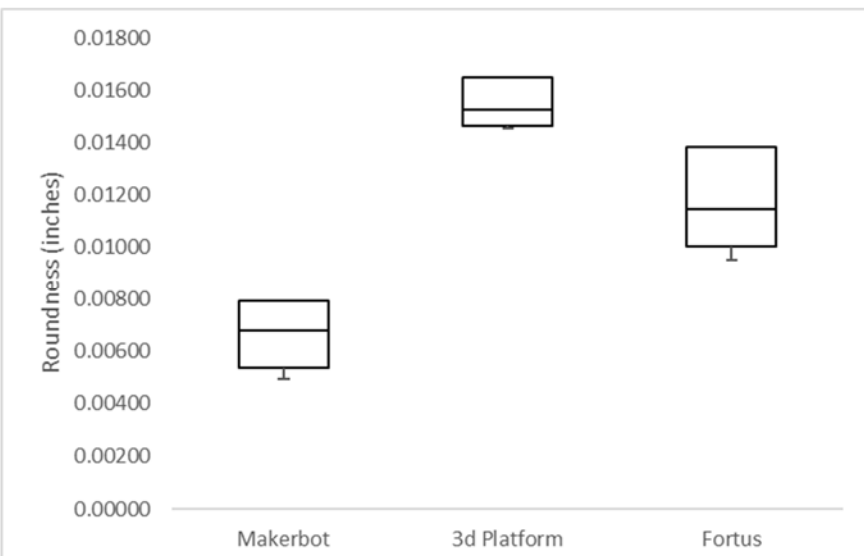

FIGURE 4. 45 Recessed cone box and whisker plot for all base, middle and bottom roundness measurements grouped together for each printer

Table 4.3 summarizes the roundness measurement results of the three 3D printers for the raised and recessed cylinder, cone and hexagonal prism. The roundness measurements were ranked as the diameter and position error measurements were ranked. Roundness measurements were ranked by accuracy, the best accuracy meaning the roundness measurement is closest to zero and is also closest to the CAD model. The roundness measurement closest to zero would represent being closest to the CAD model. The roundness measurements are also ranked based upon, consistency or repeatability. For consistency, test blocks were only compared to test blocks printed by the same printer. The closer the measurements are to the other for the specific printer, the more consistent the printer. The various performance metrics for the printers were ranked with the best performer being given a 3 and the worst being given a 1. If any printers were close in accuracy or consistency then both or all printers received the same rating. The overall rank closest to 3 had the best performance and the rank closest to 1 is the worst performance.

TABLE 4. 3 Printer rank of roundness measurements for accuracy and consistency/repeatability

	3D PRINTER		
ROUNDNESS – Accuracy	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Raised Cylinder	1	2	3
Recessed Cylinder	2	1	3
Raised Hexagonal Prism	N/A	N/A	N/A
Recessed Hexagonal Prism	N/A	N/A	N/A
Raised Cone	1	2	3
Recessed Cone	1	2	3
ROUNDESS AVERAGE RANK – Accuracy	1.25	1.75	3.00

ROUNDNESS - Consistency/Repeatability	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Raised Cylinder	1	3	3
Recessed Cylinder	1	2	3
Raised Hexagonal Prism	1	2	3
Recessed Hexagonal Prism	2	1	3
Raised Cone	1	3	3
Recessed Cone	3	3	1
ROUNDNESS AVERAGE RANK – Consistency	1.50	2.33	2.67

4.2.4 Summary of dimensional accuracy and consistency/repeatability

Summary of all measurement types by accuracy and consistency/repeatability listed in table 4.4.

TABLE 4. 4 Overall printer rank by feature and accuracy and consistency/repeatability

	3D PRINTER		
Accuracy	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
DIAMETER	1	2.5	2.5
POSITION ERROR	1.50	2.17	3.00
ROUNDNESS	1.25	1.75	3.00
AVERAGE OVERALL RANK - Accuracy	**1.25**	**2.14**	**2.83**

Consistency/Repeatability	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
DIAMETER	1.67	2.00	2.67
POSITION ERROR	1.67	2.17	2.83
ROUNDNESS	1.50	2.33	2.67
AVERAGE OVERALL RANK - Consistency	**1.61**	**2.17**	**2.72**

4.3 Total Print Time

The printer run times for each of the three printers were summarized in table 3.2 to be able to compare to the printer settings but are also summarized below in table 4.5. The total run time includes printing three blocks but for comparison the total run time was divided by three to compare to the total run time for three blocks to printing one block. Overall, the MakerBotz18s took the longest to complete by more than double of the 3D Platform and Fortus 450 printers. But the 3D Platform and Fortus 450 printers were very close in time. For the Fortus 450 printer infill is not a parameter that can be specifically input. The options are to print Solid (100% infill), Sparse (calculated approximately 38% infill) and Sparse – Double Dense (calculated to be approximately 54% infill). The total run time below for the Fortus 450 is based upon the Sparse – Double Dense setting of approximately 54% infill while the 3D Platform printer is at 40% infill.

TABLE 4. 5 Total printer run time for each printer

3D Printer	Total Run Time (3 Blocks)	Run Time (1 Block)	Infill
MakerBotz 18s	15 h 19m	5 h 6m	40%
3D Platform	6 h 53m	2 h 17m	40%
Fortus 450 – Sparse -Double Dense	6 h 24m	2 h 8m	~ 54%
Fortus 450 - Sparse	1 h 30m	30m	~ 38%

In order to compare a total time for the Fortus 450 at the Sparse setting with an approximate infill of 38%, an estimate was provided by the Fortus 450 print software to be an approximate print time of 1 hour and 30 minutes for three total test blocks, 30 minutes for one test block. Therefore, overall the Fortus 450 printer is the fastest, followed by the 3D Platform and the MakerBotz 18s printers, respectively. However when comparing all three printer to an infill near 40% the Fortus 450 is nearly five times faster than the 3D Platform, while the 3D Platform is almost twice as fast as the MakerBotz18s.

CHAPTER 5 CONCLUSION

In this paper, three 3D printers were compared at three different cost ranges. The three printers chosen were the MakerBotz 18s (entry level), the 3D Platform (intermediate level) and the Fortus 450 (commercial level). Three identical test blocks were printed on each of the printers. Measurements were taken to analyze how surface roughness, dimensional accuracy and consistency, and total printer build time vary based upon the three 3D printers.

There was not a significant difference in measurements between the three printers for average surface roughness measured on the side of the test blocks. The 3D Platform had more variance in the surface roughness between its three test blocks than the other two printers. It was determined the front side of one of the test blocks had a gap between two layers of the filament bead which resulted in inconsistent results. The measurements were then retaken on the back side, which showed consistent measurements between the 3D Platform test blocks. On the bottom of the test block, the 3D Platform had a very low average surface roughness compared to the other two printers, however this was due to the 3D Platform having a heated build plate. The measurements were retaken on the top surface to better compare to the Fortus 450 and the MakerBotz 18s. The average surface roughness on the top of the 3D Platform test blocks was the least rough when compared to the other printers. The Fortus 450 surface roughness was rougher than the 3D Platform, however not significantly rougher. The MakerBotz 18s had the roughest surface roughness. The rank of the three printers based upon the results of the average surface roughness on the side and bottom/top are shown in figure 5.1.

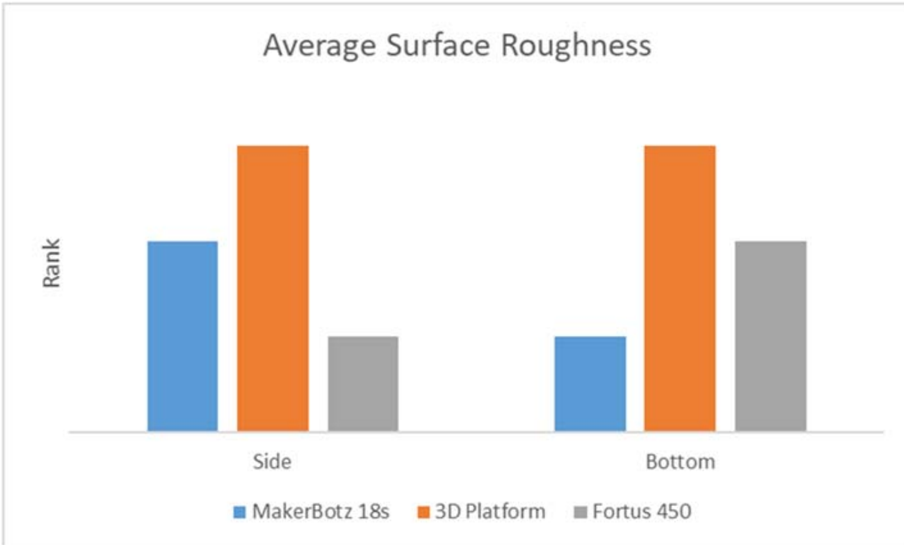

FIGURE 5. 1 Average surface roughness printer rank for side and bottom of test block. The higher the rank, the better the surface roughness.

For dimensional accuracy and consistency, measurements of diameter, position error, and roundness were taken for each of the test block features: raised and recessed cylinder, hexagonal prism and cone. Summary of the accuracy measurements for each measurement type are shown below in figure 5.2. The Fortus 450, the commercial printer, performed best for position error and roundness accuracy, but had very similar results to the 3D Platform printer for diameter accuracy. The MakerBotz 18s, the entry level printer, performed the worst in all three measurement types. For diameter accuracy, the measurements were much smaller than the CAD model when compared to the other two printers.

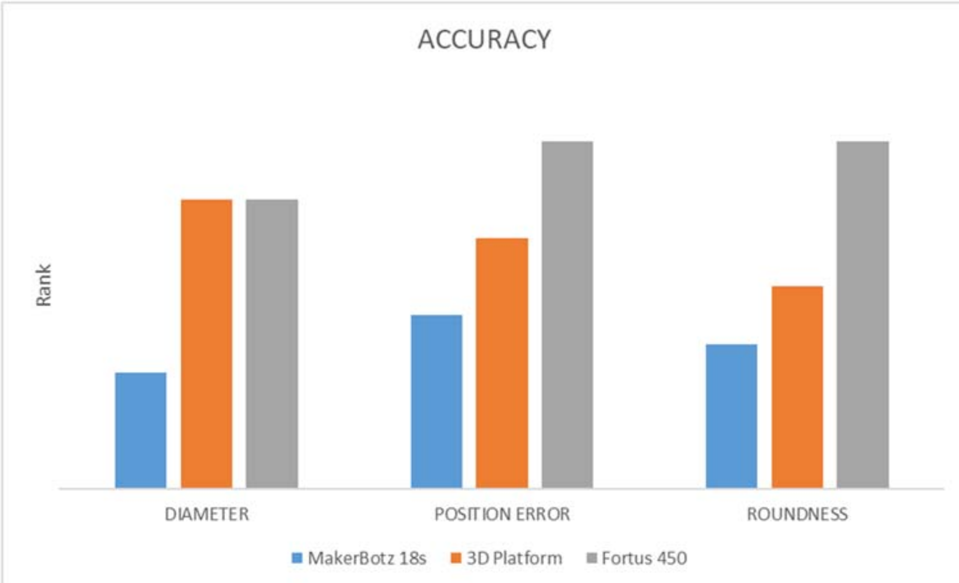

FIGURE 5. 2 Accuracy printer rank for diameter, position error, and roundness. The better the accuracy, the higher the rank.

The summary of the rank for each printer by measurement type based on consistency is shown in figure 5.3. The Fortus 450 performs the best for all three measurement types: diameter, position error and roundness. The 3D Platform next best for all three measurement types, then followed by the MakerBotz, the worst performance for all three measurement types.

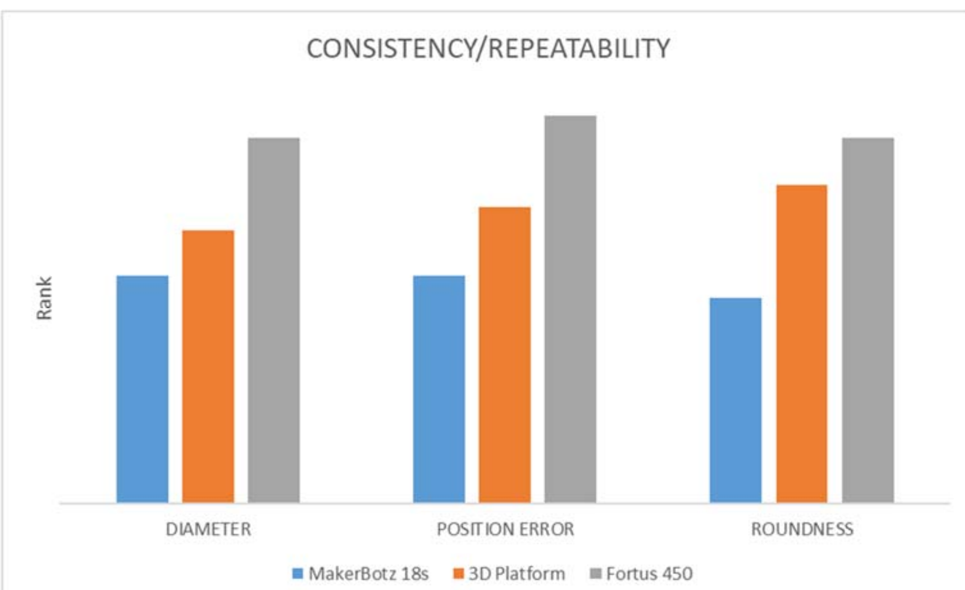

FIGURE 5. 3 Consistency/Repeatability printer rank for diameter, position error, and roundness. The higher the bar, the better the accuracy.

Overall, the Fortus 450 is ranked the highest for both dimensional accuracy and consistency, follow by the 3D Platform and the MakerBotz 18z. The summary of the results also shown in figure 5.4.

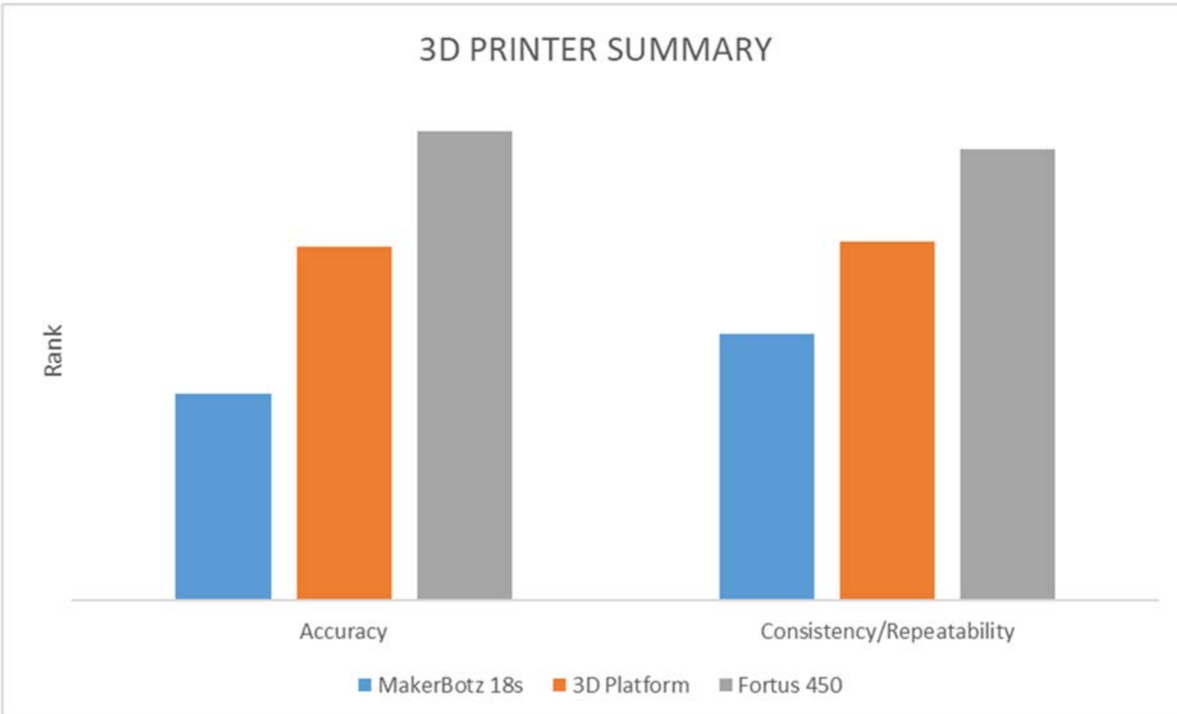

FIGURE 5. 4 Overall printer rank by accuracy and consistency/repeatability. The higher the rank the better the accuracy and consistency/repeatability

For printer build time, the Fortus 450 printed the test block nearly five times faster than the 3D Platform. But even though the 3D Platform printer was slower than the Fortus 450, it still printed almost twice as fast as the MakerBotz 18z. Results shown in figure 5.5.

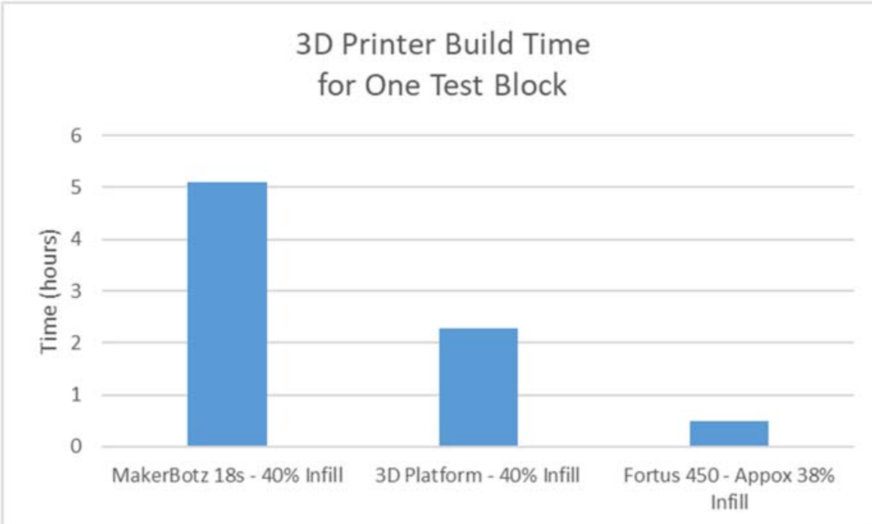

FIGURE 5. 5 Printer build time for one block

Overall, the results show little accuracy improvement with increasing printer cost, therefore it is clear that the main improvement gained by the increased cost is increased speed. Since the Fortus 450 is a commercial printer and is used for production, speed is definitely an important attribute. The Fortus 450 also performed best in accuracy for position error and roundness, and also best for consistency and repeatability for all three measurement types. The 3D Platform printer also still provides a significant increase in speed compared to the MakerBotz 18s, and is a seventh of the cost of a Fortus 450 and the 3D Platform performed fairly comparably when comparing dimensional accuracy and consistency measurements. The 3D Platform did show a frequent decrease in accuracy as the build height increased. The MakerBotz 18s is an entry level 3D printer and is about a fourth of the cost of the 3D Platform, and even though the print time was much longer, if the printer is not in a production environment this may be an acceptable option. Overall, for dimensional accuracy, not one specific printer stood out significantly above the other.

In general, surface quality for 3D printers need improvement and the results of the average surface roughness measurements described here show this. The best overall average surface roughness measurement were taken on the side of the test blocks. And the bottom and top average surface roughness measurements were significantly larger when compared to the side measurements. The 3D Platform showed the best average surface roughness results for measurements taken on the top and bottom of the test block. Next was the Fortus 450 and the MakerBotz 18s, respectively. One aspect of the Fortus 450 that is notable is the Fortus 450 had very consistent average surface roughness measurements taken on the bottom of the test block in three different directions and visually had the most consistent surface with minimal or no gaps between the filament beads.

TABLE 5. 1 Summary of result

	PRINTER		
FACTOR	**MakerBotz 18s**	**3D Platform**	**Fortus 450**
Cost	Lowest, $6,500	Moderate, $30,000	Highest, $230,000
Surface Quality	Roughest bottom surface with many gaps between filament bead	Smoothest bottom surface due to heated build plate Moderate gaps between filament bead	Best Surface Quality Most consistent with minimal gaps between filament Consistent average surface roughness measurements in three directions
Dimensional Accuracy No significant difference between printers	Worst	Moderate	Best, most improvement with position error
Consistency/Repeatability Accuracy No significant difference between printers	Worst	Moderate, Frequent decrease in accuracy in z-direction	Best, most consistency overall
Print time - one block	Slowest, 5 h 6 m	Middle, 2 h 17 m	Fastest, 30 m - Sparse setting

Overall, choosing a 3D printer requires understanding one's intended use and needs regarding cost, surface quality, accuracy, consistency, and total print time. If cost is the driving factor then the MakerBotz 18s is probably an acceptable option if there is some flexibility on surface quality consistency and the long print time is manageable. If there is a need for a shorter print time, then the 3D Platform reduces time by half of the MakerBotz 18s, but is also over four times the cost of the MakerBotz 18z. The dimensional accuracy results of the 3D

Platform did not show a significant improvement in accuracy over the MakerBotz 18s, and 3D Platform did show a frequent decrease in accuracy as the build height increased. But the 3D Platform did show visual improvement in surface quality consistency over the MakerBotz 18s. If cost is not a driving factor, but total print time is an important aspect, then the Fortus 450 provides nearly a five times decrease in total build time when compared to the 3D Platform but the cost of the Fortus 450 is over seven times the cost of the 3D Platform. The Fortus 450 did not show significant improvement in dimensional accuracy over the other two printers. But it did have the best consistency/repeatability in accuracy, and had consistent average surface roughness in three different directions on the bottom surface of the test blocks. The Fortus 450 visually showed the best consistency, with little or no gaps in the filament bead, in surface quality over the entire surface of the test block. Summary of the results can be found in table 5.1. But overall, the best printer to choose will depend upon how important cost, surface quality, dimensional accuracy, consistency/repeatability, and total print time are to the project.

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