Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 4, No.2, October 2022, pp. 0220212-01 ~ 0220212-07
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v4i2.12950

Significance of Fundamental Metrology of 3D-Printed Parts for Engineering Design: Dimensional Accuracy

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Abstract. This paper discusses some basic metrology considerations when 3D printing. The importance of ensuring correct measurements is highlighted especially for practical applications. The last part of the paper presents sample dimensional measurements of 3D-printed parts with varying sizes, infill density and layer thickness. Different cube sizes of 10 mm^3, 15 mm^3, and 20 mm^3 has been produced using a commercially-available 3D printer. Acrylonitrile butadiene styrene (ABS) has been used for the experiments. Important observations and insights are presented. The effect of layer thickness, infill density and specimen size on the dimensional accuracy of 3D-printed polymer parts have been investigated. It was found out that as the layer thickness increases, the accuracy of measured values decreases, and as the infill density increases, the accuracy of measured values also increases.

Keywords: 3D Printing, Additive Manufacturing, Acrylonitrile Butadiene Styrene, Metrology, Dimensional Accuracy

(Received 2022-08-25, Accepted 2022-10-31, Available Online by 2022-10-31)

1. Introduction

Additive Manufacturing (AM) or 3D Printing, has emerged as an alternative and complement for conventional manufacturing processes. 3D Printing techniques have been developed to cheaper and faster ways of production with high quality output. These advancements have changed the way products are produced and used by both manufacturers and consumers. With AM, manufacturing period have actually been reduced from several weeks to a matter of hours while reducing production cost and improving efficiency of manufacturing [1]. For these reasons, AM is now being used in a wide range of applications such as in electronics, robotics, construction, automotive, agriculture, medicine, aerospace, desalination, education, satellites, oil & gas, and many others [2]–[15]. The widespread application of AM is being hindered by the limited number of available guidelines for metrology and inspection [16]. For practical engineering applications, 3D-printed parts should be accurate in terms of measurement [17]–[26] and should also withstand various amounts of mechanical and environmental stresses [1, 27]. It is important to achieve results similar to outputs manufactured using traditional methods [26], [28]. Fused Deposition Modelling (FDM), which is one of the most common 3D printing technologies, has a principle similar to a glue gun, wherein layers of thermoplastic material are extruded in the semi-molten state. Common materials being used for FDM include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polycarbonate (PC), thermoplastic polyurethane (TPU), and others. Metrology pertains to measurement methods, standards, accuracy, precision and uncertainties, and other measurement concepts [29]. It includes the equipment, the measurements and analysis of obtained data [30]. Metrology involves the establishment of units, development of measurement protocols, production of artifacts to allow traceability of measurements, and analysis of measurement accuracies and uncertainties [31]. Metrology includes measurements quantified with numbers and of course expressed in units. The following are some of the common metrology methods: 1) Dimensional Metrology which includes Linear Measurement, Angular Measurement, Comparator; 2) Surface Metrology (Surface Roughness); 3) Coordinate Metrology which includes Coordinate Measuring Machine, Multilateral Optical GPS, X-ray Computed Tomography, Automated Inspection, Machine Vision and Magnetic Resonance Imaging; 4) Geometrical Dimensioning and Tolerancing (GD&T) includes roundness, flatness, straightness, etc.; and 5) Measurement of Material Properties [16].

One of the major issues in 3D printing technologies is the dimensional accuracy of the 3D-printed outputs. Dimensional accuracy is a vital aspect in any manufacturing and production process as it is a clear indicator of how exact a fabricated part is with reference to the designed part. Along with accuracy in dimension, tolerance is also important due to application of parts in assemblies. [19]–[22]. FDM offer several advantages but is still limited since only a few have analyzed the dimensional accuracy of FDM/FFF-produced parts and along with the effect of slicing parameters on the printed product [21], [26]. Several groups have already conducted studies on the metrology of 3D-printed parts. Ali compared the accuracy of two different 3D printing materials (ABS and PLA), and observed that there is no significant difference in the accuracy of the measured dimensions of the two materials [32]. Carneiro et al. studied the effects of 3D printing parameters such as the infill density, layer height and raster orientation in polypropylene produced via the FDM process. Their work concluded that layer height has less impact on the properties of the final output [33]. In another work, Robertson et al. studied the dimensional accuracy of 3D-printed parts produced by the MakerBot Replicator 2. However, effects of parameters such as the orientation, layer thickness and infill density were not studied. Mahesh et al. analyzed geometries through free form surfaces wherein deviations from the set dimension ranging from 5% to 15% were discovered [34]. Wang et al. [35] developed a process tool for the modification of the effects of parameters. Post-processing methods were also observed to create change in surface quality, these changes are attributed to manual or chemical changes in the material itself [33]–[34], [36]. More sophisticated measurement techniques have also been employed by various groups. Yankov et al. 3D-printed micro-squares using an SLA 3D printer. They measured the coordinates of the objects using a Carl-Zeiss optical microscope. The acquired micrographs were used to measure the micro-grid deviations of the objects. They observed higher and irregular deviations from CAD values depending on the location of the object on the build plate [37]. Li et al. developed a method for layer-by-layer mapping of 3D printed parts using a high-speed optical scanning system integrated in an FDM 3D printer. This set-up could scan the object during the printing process to validate and conduct in situ adjustment of the 3D printing parameters [38]. Kacmarcik et al. investigated the form, size, orientation and location accuracy of the FDM 3D-printed parts using a coordinate measuring machine (CMM). They observed that the commercially-available 3D printer demonstrates higher accuracy than the home-made 3D printer. [39]. Dardzinska et al. measured the dimensional accuracy of 3D-printed parts using computed tomography (CT) and 3D scanner. The authors provided insights comparing different 3D printing methods such as Polyjet and FDM among others [40]. Jadayel et al observed improved accuracy using this three-dimensional metrology feedback and mesh morphing. The authors used a 3D geometric compensation method to eliminate systematic deviations by morphing the object's original surface mesh model by the inverse of the systematic deviations. Multiple sacrificial 3D-printed objects were scanned to measure the systematic deviations, and the average deviation vector was computed throughout the model [41]. While there are a lot of aspects that must be considered in studying the dimensional accuracy of parts, one of the least studied in the past is the size of the specimen or samples. It has been observed that the size of the specimen has an impact on its mechanical properties. This occurrence is known as the 'size effect' [42]. Recently, the authors used a factorial design to evaluate the optimal combinations of different sizes, layer thickness and infill density to ensure dimensional accuracy of the 3D-printed parts [43], [2]. The aim of this study is to assess the accuracy of 3D printed parts and understand the effects of specimen size as well as the printing parameters such as layer thickness and infill density.

2. Materials and Methods

ABS filament, a proprietary acrylonitrile butadiene styrene (ABS) material made by Zortrax, has been used in the study. A description regarding ABS has been reported elsewhere [43].

The specimen in the form of cubes were designed using Autodesk Inventor with reference to the previous work done by authors [43]. The designed part was exported to .stl format to prepare it for the slicing process in Z-Suite which a slicing software dedicated for the Zortrax M-200 3D Printer. The slicing process involves the modification of parameters such as the size, layer thickness and infill density. The sizes were printed with size variations – 10 mm3, 15 mm3and 20 mm3; for layer thickness – 0.9 mm, 0.19 mm and 0.39 mm. Lastly, the infill density were varied with ranges 0.09 mm, 0.19 mm and 0.39 mm. A Zortrax M200 FDM 3D Printer was used to print the samples. The dimension of the cubes was then quantified using a Mitutoyo Digimatic Micrometer and a Mitutoyo Digimatic Vernier Caliper shown in a recent study published elsewhere [43]. The manual measurement of the cubes provided important insights on the variation in dimensions due to variation of the parameters. The cubes were measured in an array of positions, i.e. (1) top-to-bottom (2) front-to-back and (3) left-to-right. The locations where the samples were measured have also been presented elsewhere [43]. In this paper, the measured values are said to be accurate if their average values are close to the designed values (of $10mm^3$, $15mm^3$ and $20mm^3$). Also, the measured values are said to be precise if the computed standard deviation is relatively small.

3. Results and Discussion

The average values of the measurements are shown in Table 1. It shows the measured values using the Digital Micrometer and those measured values using the Digital Vernier Caliper.

Several effects are observed under the following conditions

1. Effect of layer thickness on the dimensional accuracy: As the layer thickness increases, the accuracy of measured values decreases. Hence, with a layer thickness of 0.09 mm we can expect a relatively higher accuracy compared with the 0.39 mm layer thickness.
2. Effect of infill density on the dimensional accuracy: The data shows some scattering, but it may be safe to say that as the infill density increases, the accuracy of measured values also increases. This could mean that the infill materials serve as support structures which ensure the accurate placement of all the layers of the 3D-printed parts.
3. Effect of sample size on the dimensional accuracy: It can be observed also that as the size of the 3D printed object increases its dimensional accuracy also increases.

Table 1. Measured dimensions using a Digital Micrometer

		Digital Micrometer Caliper					Digital Vernier Caliper				
Print Parameter	Size	Top to Bottom Average	Front to Back Average	Left to Right Average	Average Size per Specimen	Standard Deviation per Specimen	Top to Bottom Average	Front to Back Average	Left to Right Average	Average Size per Specimen	Standard Deviation per Specimen
0.09 Thickness 30% Density	10mm	10.09	9.99	9.96	10.01	0.05	10.08	10.17	10.01	10.09	0.07
	15mm	15.07	15.02	14.97	15.02	0.04	15.10	15.13	15.13	15.12	0.01
	20mm	20.06	20.04	19.92	20.01	0.06	20.09	20.01	19.92	20.01	0.07
0.09 Thickness 60% Density	10mm	10.04	9.98	10.04	10.02	0.03	10.02	10.07	10.13	10.07	0.05
	15mm	15.01	14.94	15.00	14.98	0.03	15.05	15.07	15.14	15.08	0.04
	20mm	20.02	19.90	20.02	19.98	0.06	20.02	20.03	20.14	20.06	0.05
0.09 Thickness 90% Density	10mm	10.04	10.01	10.03	10.03	0.01	10.05	10.13	10.10	10.10	0.03
	15mm	15.00	14.96	15.02	15.00	0.02	15.03	15.11	15.13	15.09	0.04
	20mm	19.98	19.91	20.04	19.98	0.05	20.02	20.06	20.12	20.07	0.04
0.19 Thickness 30% Density	10mm	10.08	10.04	10.05	10.06	0.02	10.03	10.09	10.18	10.10	0.06
	15mm	15.02	14.97	15.03	15.01	0.03	14.98	15.05	15.16	15.07	0.07
	20mm	20.01	19.92	20.00	19.98	0.04	19.96	20.06	20.11	20.04	0.06
0.19 Thickness 60% Density	10mm	10.08	9.99	10.12	10.06	0.05	10.08	10.14	10.11	10.11	0.03
	15mm	15.06	14.99	14.93	14.99	0.05	15.09	15.18	15.16	15.14	0.04
	20mm	20.05	19.94	19.87	19.95	0.07	20.07	19.99	20.12	20.06	0.05
0.19 Thickness 90% Density	10mm	10.05	10.00	10.02	10.02	0.02	10.06	10.10	10.15	10.11	0.04
	15mm	15.03	14.93	15.00	14.99	0.04	15.06	15.08	15.19	15.11	0.05
	20mm	20.03	19.90	20.02	19.98	0.06	20.05	20.02	20.18	20.09	0.07
0.39 Thickness 30% Density	10mm	10.27	10.15	10.17	10.20	0.05	10.23	10.09	10.09	10.14	0.06
	15mm	14.91	15.01	15.10	15.01	0.08	14.89	15.05	15.16	15.03	0.11
	20mm	19.98	19.99	20.07	20.01	0.04	19.97	19.99	20.08	20.01	0.05
0.39 Thickness 60% Density	10mm	10.28	10.20	10.19	10.22	0.04	10.23	10.07	10.08	10.12	0.07
	15mm	14.66	15.06	15.10	14.94	0.20	14.94	15.12	15.09	15.05	0.08
	20mm	19.99	20.03	20.09	20.04	0.04	19.94	19.97	20.08	20.00	0.06
0.39 Thickness 90% Density	10mm	10.12	10.08	10.03	10.07	0.04	10.06	10.21	10.12	10.13	0.06
	15mm	15.04	15.06	14.97	15.02	0.04	15.06	15.22	15.01	15.09	0.09
	20mm	20.03	20.07	19.93	20.01	0.06	19.99	20.05	20.04	20.03	0.03

Table 2. Summary of the Average Standard Deviations of the measured dimensions

Thickness	**Ave. SD**	**Density (%)**	**Ave. SD**	**Size**	**Ave. SD**
0.09	0.04	30%	0.05	10 mm^3	0.04
0.19	0.05	60%	0.06	15 mm^3	0.06
0.39	0.07	90%	0.04	20 mm^3	0.05

Table 2 shows the summary of the average standard deviation of the measured dimensions for each condition. The standard deviation (SD) describes the data dispersion from the average value from each print setting/parameter. We can use this standard definition if we want to understand other factors such as precision and variability. It can be observed that the variability of data increases as the layer thickness and specimen size increases, while it can be said that generally, the variability decreases while the infill density increases. It should be pointed out that contrary to the accuracy measurements, the variability of data is affected differently by the specimen sizes. The reason could be that the accuracy and variability of measured dimensions depend on the type and calibration of the 3D printer. More investigations are needed in order to understand the cause of this difference.

Conclusion:
In this paper, the effect of layer thickness, infill density and specimen size on the dimensional accuracy of 3D-printed polymer parts have been investigated. It was found out that as the layer thickness increases, the accuracy of measured values decreases, and as the infill density increases, the accuracy of measured values also increases. Lastly, as the size of the 3D printed object increases its dimensional accuracy also increases. Discussions on variability of data (and thus precision) using standard deviation values have also been included. It was observed that the variability of data increases as the layer thickness and specimen size increases, while it can be said that generally, the variability decreases while the infill density increases.

Acknowledgments: The authors would like to thank the support of the The Department of Science and Technology – Philippine Council for Industry, Energy, and Emerging Technology Research and Development (DOST-PCIEERD) and the Research and Development Office of the Bataan Peninsula State University (BPSU).

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