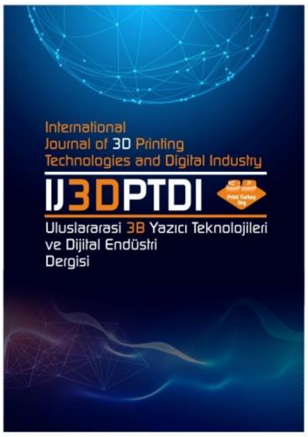

ULUSLARARASI 3B YAZICI TEKNOLOJİLERİ
VE DİJİTAL ENDÜSTRİ DERGİSİ
INTERNATIONAL JOURNAL OF 3D PRINTING
TECHNOLOGIES AND DIGITAL INDUSTRY

ISSN:2602-3350 (Online)
URL: https://dergipark.org.tr/ij3dptdi

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Yazarlar (Authors): Binnur Sagbas, Ozgur Poyraz*, Numan Durakbasa

Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): *Sagbas B., Poyraz O., Durakbasa N., "A Comparative Study on Precision Metrology Systems For Additive Manufacturing" Int. J. of 3D Printing Tech. Dig. Ind., 7(1): 114-123, (2023).*

DOI: 10.46519/ij3dptdi.1206753

Araştırma Makale/ Research Article

Erişim Linki: (To link to this article): https://dergipark.org.tr/en/pub/ij3dptdi/archive

A COMPARATIVE STUDY ON PRECISION METROLOGY SYSTEMS FOR ADDITIVE MANUFACTURING

Binnur Sagbas[a], Ozgur Poyraz[b]*, Numan Durakbasa[c]

[a]Department of Mechanical Engineering, Yildiz Technical University, Istanbul, Turkiye
[b]Department of Mechanical Engineering, Eskisehir Technical University, Eskisehir, Turkiye
[c]Research Group for Production Metrology and Adaptronic Systems, Institute for Production Engineering and Laser Technology, TU Wien, Vienna, Austria

* *Corresponding Author: ozgurpoyraz@eskisehir.edu.tr*

(**Received:** 22.11.2022; **Revised:** 09.03.2023; **Accepted:** 26.04.2023)

ABSTRACT

This paper presents a comparative study on precision metrology systems such as Coordinate Measuring Machine (CMM), 3-Dimensional Scanning (3DS) and Computed Tomography (CT) for polymer additive manufacturing. A special test sample was designed and manufactured by Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) AM systems. The manufactured parts were then measured by three different precision metrology systems and the results were compared in terms of different measurement and AM methods. Uncertainty analyses were conducted based on the results of CMM measurements. The benchmark highlighted the difference between part characteristics manufactured by FDM and SLS, where FDM part represented higher surface roughness and more deviation to the nominal design. Furthermore, expanded uncertainties computed for the FDM manufactured part were almost three times of the uncertainties computed for the SLS manufactured part. It was also demonstrated that one of the major contributors to the expanded uncertainty occurred because of rougher surface of FDM manufactured part. Similar tendency of part to nominal deviations were observable in all metrology systems including CMM, CT and 3DS. Findings of the study revealed the need of standardized measurement for inspection and control of AM parts.

Keywords: 3-Dimensional Scanning (3DS), Coordinate Measuring Machine (CMM), Computed Tomography (CT), Additive Manufacturing (AM), Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS).

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1. INTRODUCTION

Additive manufacturing, also known as "3-dimensional (3D) printing" or "rapid prototyping", is a group of emerging process technologies. AM enables its users to produce high-value, lightweight, complex, and individually customized components without significant increase in production costs [1]. In contrast to conventional manufacturing techniques, AM accomplishes its success through joining materials to make objects from 3D model data usually layer upon layer [2]. In this way, the need for using cutters for traditional machining or molds/dies for injection/deformation processes is eliminated. On top of aforementioned design advantages, AM working principle provides flexibility in production volumes, reduces design-to-production lead times and allows the application of different materials even for a single component. AM, which is categorized into seven major classes can be applied for various material families such as polymers, metals, ceramics and their composites [2], [3].

Among the so-called material families, polymer materials are being developed since the first introduction of the AM technology, and for the current state-of-the-art both thermosetting and thermoplastic polymers are available to process [4]. Furthermore, many of the AM classes have the ability to process polymers including photopolymerization, powder bed fusion, material extrusion, material jetting and binder jetting. On the other hand, powder bed fusion and material extrusion-based AM technologies are reported to provide good strength, and thus they are utilized for functional parts production in addition to prototype manufacturing [4], [5]. However, there are still challenges to be overcome in miscellaneous research areas including product design, process parameter optimization, material characterization and component verification.

Component verification is of critical importance to the end users and industry in terms of functional part production. It practices all the issues related with the design specifications covering material, physical and geometrical properties. However, there are many gaps on the inspection and quality assurance of complex AM components in terms of geometrical and dimensional properties [6], [7]. Studies are being conducted to fill these gaps and researchers evaluate AM components by means of different measurement techniques including Coordinate Measuring Machine (CMM), 3D Scanners (3DS) and Computed Tomography (CT) [8]-[12]. Minetola et al. adopted ISO 286 standard and conducted CMM measurements for verification and benchmarking of low cost Fused Deposition Modeling (FDM) machines based on a reference part [9]. Authors of the study highlighted the importance of inspection and came up with the results showing that the accuracy of FDM process is influenced by filament and nozzle diameter. In another study conducted on metrology of FDM parts, Sagbas and Durakbasa characterized specially designed test artifacts by optical systems instead of CMM and accentuate the faster inspection opportunity with optical systems [6]. Gillaugh et al. captured the geometrical characteristics of a turbo engine stream vane component by optical systems using structured light [10]. Poyraz et al. presented a specially designed and additively manufactured test artifact for surface roughness characterization, and benchmarked tactile systems with the optical ones to show the differences on curved surfaces [7]. Furthermore, Liou et al. employed optical vision systems during AM process and alter process parameters according to the received information from the optical system [11]. Stavroulakis and Leach reviewed optical form metrology for industrial-grade metal additive manufactured parts and emphasized the research needs on new metrology tools, procedures, tolerancing rules and characterization methods for to cope with the complexity of AM parts [12]. Additional works on CT systems were also presented to capture the geometrical characteristics of internal surfaces or porosities of AM produced parts [13], [14]. In depth assessment on application of CT measurement for high quality metal additive manufacturing was studied by Du Plessis and lattice structures were included on top of geometrical features [15]. CT and CMM was also applied to benchmark stereolithography and Selective Laser Sintering (SLS) by Shah et al. [16]. Finally, CT and CMM was applied for the verification of high-speed sintering AM produced parts by Gomez et al. considering the uncertainty values [17].

Although research have been done about the subject, there is still lack of standards, scientific or industrial procedures for identification of optimum measurement system for novel AM processes to consider the characteristic of AM technology, specifications of measurement systems, available accuracy, risk of uncertainties and the ease of inspection activities [8], [12].

This paper presents a comprehensive study on the metrology for functional polymer AM components. In this respect, a special test part was designed and manufactured by FDM and SLS additive manufacturing systems to provide a benchmark for different part characteristics considering low and high-cost polymer AM processes. The manufactured test parts were then measured by CMM, 3DS and CT precision metrology systems, and the results were compared in terms of different measurement and AM methods. Uncertainty analysis per JCGM 100:2008 were conducted based on the results of repeated CMM measurements [13]. To the authors' knowledge, there is no study comparing FDM and SLS AM methods by three precision measurement systems in terms of dimensional accuracy. With these aspects, this study, which provides novel and important contributions to scientific knowledge, presents the comparison of two different polymer additive manufacturing methods with three different measurement systems.

2. MATERIALS AND METHOD

2.1. Test part design

The use of benchmark and test parts have found a widespread application area among AM research, and they have been used for various purposes including machine selection, AM process comparison, parameter optimization and production strategy evaluation [18]. The developed artifacts were able to asses minimum feature size, repeatability, surface quality, dimensional and geometrical accuracy of the processes [19], [20]. In this study, the test part used for the comparisons was designed to meet a set of criteria in terms of manufacturing and metrology (see Fig. 1). In this regard, the outer dimensions of the parts were kept as minimum as possible to fit into the build volume for most of the FDM and SLS systems available in the market, to spend less material and to be manufacturable in a relatively short cycle time. In addition to that, metrological evaluation was considered during design as the main aim of the study. For this reason, it was designed as stiff as possible to avoid warping effects and thinner sections were excluded from the part. Moreover, test part was designed with a constant cross section perpendicular to the build direction, and by this way the need for support structures was eliminated and the risk for stair stepping effect was reduced. Lastly, diversified metrological benchmark capability was provided adding different features such as holes, radii, planes and angular faces.

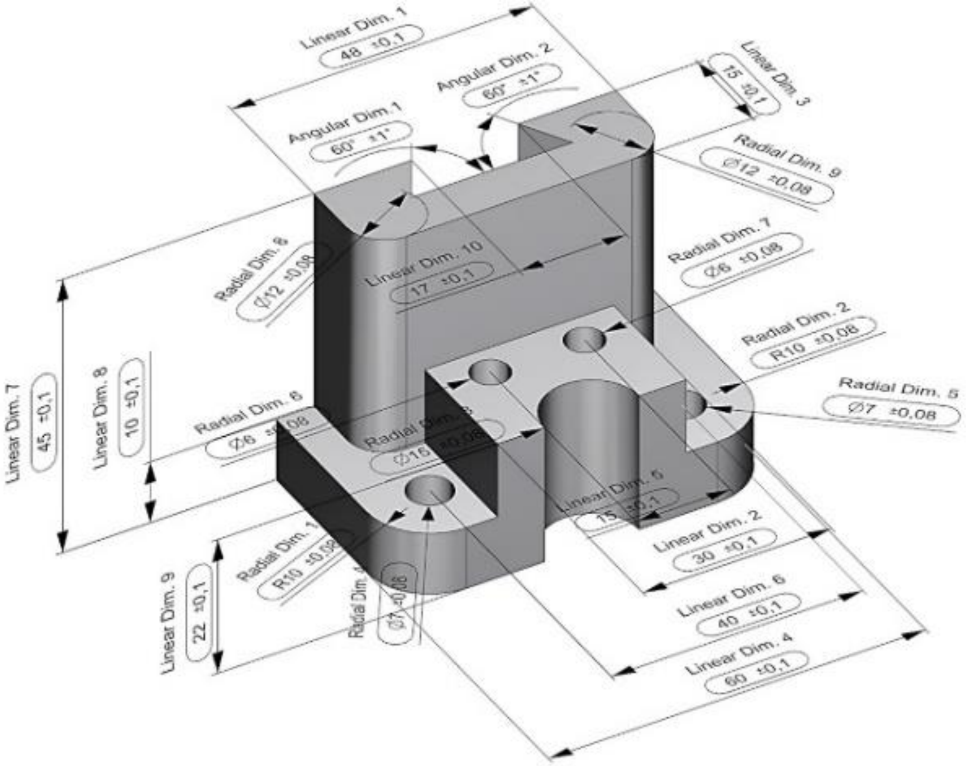

Figure 1. Test artifact with the dimensions.

2.2. Manufacturing of test artefacts

Thanks to the developments in AM technology and similar to the other material families available for AM, functional part productions of polymer materials are continuously increasing their application areas. In accordance with the purpose of functional part production, a sufficient level of strength is required and several AM techniques are reported to ensure good strength [3]. Among these, FDM and SLS are highlighted as low and high cost AM technologies considering the machine investment and material prices [4]. These two techniques were selected for the current study to benchmark two polymer AM technologies compatible for functional part production and representatives for diverse budget ranges.

FDM, also known as “fused filament fabrication”, is an extrusion-based AM technology and it feeds polymer materials in filament form by means of an extruder. The fed filament materials are melted by a heating element and extruded through a nozzle. The movable extrusion system follows part cross section in the layer plane axes and the build platform is indexed one layer down (Fig. 2a). This cycle is repeated until the part reaches its full height. On the other hand, SLS is a powder bed fusion based AM technology, and it feeds polymer materials in powder form by means of a re-coater. Part cross-section is scanned by a laser directed by mirrors. After the scanning of the part cross-section is completed, build platform moves one layer down and this cycle is repeated until the part reaches its full height (Fig. 2b). In the scope of this study, Mfact 3D printer was used as FDM and EOS P110 as SLS systems. As the part materials, typical grades for each system were selected. Acrylonitrile butadiene styrene (ABS) was applied in FDM and polyamide (PA) was applied in SLS.

The optimum process parameters recommended by the suppliers were selected for manufacturing of the sample parts. These parameters were presented consecutively in Table 1 and Table 2.

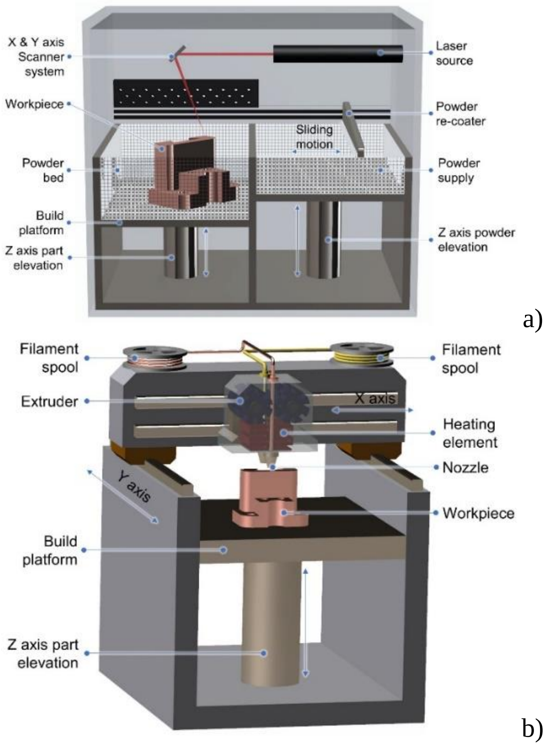

Figure 2. Working principles of a) FDM and b) SLS technologies.

Table 1. FDM process parameters.

Parameter	Unit	Value
Layer thickness	mm	0.2
Printer speed	mm/min	3000
Extruder temperature	℃	205
Shells	Number	3
Infill percentage	%	35

Table 2. SLS process parameters.

Parameter	Unit	Value
Layer thickness	mm	0.1
Scanning speed	mm/s	2500
Hatch distance	mm	0.25
Laser power	W	30

2.3. CMM Measurements and uncertainty analysis

CMM measurements in this study were carried out at the Interchangeable Manufacturing and Industrial Metrology Laboratory of the Institute for Production Engineering and Laser Technology of Vienna University of Technology. The reference temperature range of the relevant laboratory was kept at 20°C±0.1°C and relative humidity was 45%±5. In addition to these, vibration isolation was maintained and maximum ground amplitudes at frequencies greater than 5 Hz was 0.05 µm. The CMM was Aberlink Axiom Too equipped with a probe having 3 mm diameter and the parts were fixed on top of the CMM table with the help of a vise. A sample view of the CMM set-up consisting of the vise and the SLS part is given in Fig. 3 and the CMM specifications are provided in Table 3. All the geometrical features of the test sample were five times measured under the same conditions.

Figure 3. CMM set-up consisting of the vise and the part.

Table 3. CMM specifications.

Characteristic	Unit	Value
Volumetric accuracy*	µm	(2.1+0.4L/100)
Scale resolution	µm	0.1
Optimum temperature range	°C	18-22
Max velocity vector	mm/s	866
Max acceleration vector	mm/s^2	1200

* Maximum Permissible Error MPECMM according to ISO 10360-2. 2009 within the thermal limits defined for optimum temperature range.

Since the tactile coordinate metrology is commonly used a reference method, uncertainty analyses were conducted following to CMM measurements. According to related standards and guides [22], uncertainty can be estimated using two type of evaluations.

Type A evaluations estimates the uncertainty by the statistical analysis of series of observations, and in this study, repeated measurements were considered to estimate the Type A uncertainty of the CMM. First of all, average value for a series of n measurements were calculated using Eq. (1), where x is measurand and $\bar{x}$ is average value of measurements.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad (1)$$

Subsequently, standard deviation was studied using Equation (2) and is expressed with S_x.

$$S_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{(n-1)}} \qquad (2)$$

Finally, Type A uncertainty based on repeatability of measurements, u_P, was estimated using Equation (3).

$$u_P = S_x/\sqrt{n} \qquad (3)$$

In contrast to Type A evaluations, Type B evaluations estimates the uncertainty by non-statistical methods considering other issues such as measuring system, measured workpiece, environmental conditions and past experiences. Among these issues, uncertainty contributions of measuring system can be added to the combined uncertainty budget as calibration uncertainty, u_i, and can be expressed using Equation (4). MPE_{CMM} is the maximum permissible error of the CMM system and was defined in the specifications given in Table 3.

$$u_i = 0.5\, MPE_{CMM} \qquad (4)$$

Uncertainty contributions of measured workpiece and the effect of environmental conditions can be considered together as u_w and expressed using Equation (5), where u_T is the uncertainty of the work piece, caused by temperature variations and u_R is uncertainty of the workpiece caused by surface roughness.

$$u_w = \sqrt{u_T^2 + u_R^2} \qquad (5)$$

However, this study neglects the effect of temperature variations since the temperature was under tight control (20°C±0.1°C) at the laboratory where measurements were carried out. On the other hand, surface roughness was especially considered to reveal the differences between two processes in terms of metrological evaluation. For this reason, surface roughness was measured with a 5 µm diameter probe and 8 mm cut-off length, and average values $R_{z.mean} = 96.63\ \mu m$ and $R_{z.mean} = 48.5\ \mu m$ were obtained for FDM and SLS manufactured artifacts respectively. u_R uncertainty was calculated using the $R_{z.mean}$ values and Equation (6). $\sqrt{3}$ was considered following to the observations and likelihood of a rectangular distribution.

$$u_R = (R_{z.mean}/2)/\sqrt{3} \qquad (6)$$

Estimated Type A and Type B values were integrated into a single uncertainty, u_{CMM}, magnitude by combining those using Equation (7).

$$u_{CMM} = \sqrt{u_P^2 + u_i^2 + u_w^2} \qquad (7)$$

Finally, expanded uncertainty was calculated by multiplying the combined uncertainty with $k = 2$ as coverage factor for a confidence level of 95% (Equation (8)).

$$U_{CMM} = k u_{CMM} \qquad (8)$$

2.4. CT Measurements

CT scan measurements were performed in the same laboratory with the CMM measurements and Werth Tomo Scope Technology XS was used as the measurement system. The measurement system consisted of X-ray source tube, detector and a rotating table between source tube and detector. The resolution of the system was 0.1 μm and maximum permissible error MPE_{CT} was defined with $MPE_{CT} = 7.5 + L/50$ where L is the measuring length in mm comparable to ISO 10360. To construct 3D model of the measured workpiece, images were taken at different angular positions by fixing the part on the table and rotating the table between source tube and detector. Taken images were combined using the necessary algorithms provided by WinWerth® software. A sample view of CT set-up consisting of the table and the SLS part is given in Fig. 4 and CT scan parameters are provided in Table 4.

Figure 4. CT set-up consisting of the table and the part.

Table 4. CT scan parameters.

Parameter	PA2200
Voltage (kV)	146
Current (μA)	408
Filter material	Copper
Filter thickness (mm)	0.2
Voxel size (μm)	34.07

2.5. 3DS Measurements

As the last measurement system, Solutionix Rexcan 3D optical scanner was used. The system had twin camera with phase shifting optical triangulation. Laser light was projected on to the measured workpiece and by means of a beam deflecting mirror, the workpiece was scanned. Triangulation angle defines the resolution of the system and 0.003 mm was used in this study. Before the scanner was calibrated to minimize the errors, the workpiece was spray coated and target points were placed on necessary regions. ezScan and Geomegic Control-X were used as scan and evaluation software. A sample view of 3DS set-up consisting of the table and the SLS part is given in Fig. 5.

3. RESULTS AND DISCUSSIONS

Results were evaluated for the identified tolerance ranges based on the average value of selected FDM and SLS system manufacturer specifications, following to repeated CMM measurements of 14 different geometrical features (Table 5).

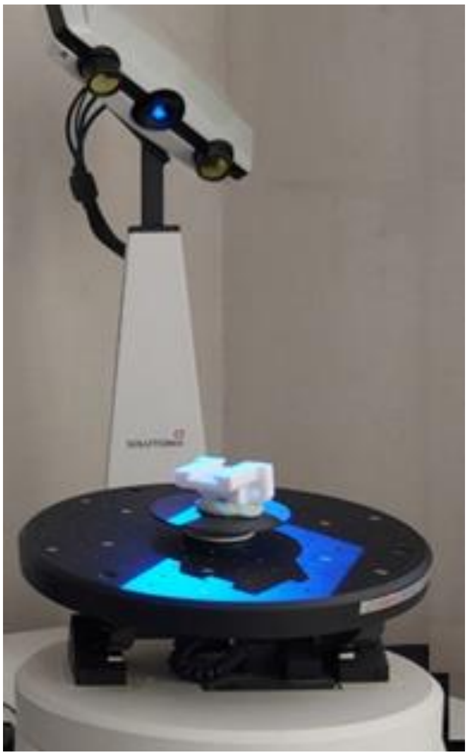

Figure 5. 3DS set-up consisting of the table and the part.

Table 5. CMM measurement results.

Dimension	Ref. Value	Tol.	FDM (ABS) Actual	SLS (PA) Actual
Angular Dim.1 (°)	60	1	60.471	61.850
Angular Dim.2 (°)	60	1	60.696	61.540
Linear Dim.5 (mm)	15	0.1	14.963	14.986
Linear Dim.6 (mm)	40	0.1	39.870	39.893
Linear Dim.7 (mm)	45	0.1	44.884	44.891
Linear Dim.8 (mm)	10	0.1	9.883	9.880
Linear Dim.10 (mm)	17	0.1	17.002	17.071
Radial Dim.1 (mm)	10	0.1	9.733	9.701
Radial Dim.2 (mm)	10	0.1	9.698	9.698
Radial Dim.3 (mm)	15	0.1	15.325	15.356
Radial Dim.4 (mm)	7	0.1	6.874	6.978
Radial Dim.5 (mm)	7	0.1	6.841	6.928
Radial Dim.6 (mm)	6	0.1	5.829	5.948
Radial Dim.7 (mm)	6	0.1	5.826	5.942

Considering the nominal value and tolerance ranges of the workpiece, both the FDM and SLS systems showed similar performance in terms of linear dimensions. On the other hand, SLS manufactured workpiece showed better performance for the curved features which were represented with the radial dimensions. For this trend, the only outlier were the angular features. The reason for this was interpreted as the lack of sufficient flat surface of FDM manufactured parts after excluding the unintended radii in the corner of the angular faces.

Uncertainty analyses were conducted for 5 selected features following to initial benchmark. Selected 5 features represent different properties like linear length, inner/outer radial dimensions and center to center distances. As can be seen from the Table 5 and Table 6, the difference between FDM and SLS manufactured parts is more pronounced in uncertainty values comparing to measurement values.

It is obvious that all the uncertainty values are elevated in FDM parts. Detailed interpretation of Table 6 reveals the major contributors to the combined uncertainty are Type A uncertainty (u_P) based on the repeatability of measurements and Type B uncertainty based on surface roughness (u_w).

Table 6. Uncertainty budgeting and benchmark for the CMM measurements in μm.

Part	Feature	u_P	u_i	u_w	u_{CMM}	U_{CMM}
FDMed part	Hole (Radial Dim.3)	30.1	2.31	13.9	33.3	66.5
	Hole to hole distance (Linear Dim.5)	1.0	2.31	13.8	14.2	28.4
	Radius (Radial Dim.1)	33.9	2.29	14.0	36.7	73.4
	Plane to plane distance (Linear Dim.7)	0.8	2.43	13.7	14.1	28.2
SLSed part	Hole (Radial Dim.3)	2.0	2.31	7.0	7.6	15.3
	Hole to hole distance (Linear Dim.5)	0.3	2.31	7.1	7.4	14.8
	Radius (Radial Dim.1)	8.8	2.29	6.9	11.5	22.9
	Plane to plane distance (Linear Dim.7)	0.4	2.43	6.8	7.2	14.4

The results of the interpretations are comparable with previous studies. Santons et al. designed, characterized and estimated a benchmark artefact using high-speed sintering additive manufacturing and estimated uncertainty values based on CMM measurements [23]. They have presented 80 μm uncertainty for a 10 mm cylinder diameter with 75 μm $R_{z.mean}$ which is a close value to the current study achieved for the Radial Dim. 3b (cylindrical hole) having 15 mm diameter [23]. Related study has also emphasized the dependence of CMM uncertainty on the surface roughness of high-speed sintering AM parts [22]. Additional to this, Zanini et al. characterized a lattice structure part of Ti6Al4V manufactured by laser powder bed fusion AM process and estimated uncertainty values based on CMM and CT measurements [24]. They reported a CT uncertainty of 45 μm by using substitution method and including the contribution of surface roughness [24]. Moreover, they highlighted the need for further investigations on multiple measurement approach whether it gives sufficient weight to the effect of surface roughness [24]. A study conducted by Minetoal et al., benchmarked three different polymer AM methods and highlighted that SLS part's dimensional accuracy is better than FFF part [25]. The authors of the study have associated the findings with the smaller layer thickness providing a better definition and higher dimensional accuracy of the part dimensions of part dimensions in line with this studies benchmark between SLS and FDM [25]. In this regard, it can be stated that increased surface roughness of FDM manufactured part leads to errors and uncertainties during tactile measurement techniques such as CMM. Fig. 6 shows a benchmark of all manufacturing and measurement systems.

In Fig. 6, horizontal axis shows the dimensional magnitude of measured feature in mm where the vertical axis shows absolute value of deviation from nominals. Table 7 shows the measurement results with CT and 3DS. The results obtained by non-tactile measurement systems of CT and 3DS were also benchmarked in the scope of this study. As can be observed from Table 7 and Fig. 6, similar tendency of higher deviations in FDM manufactured parts can be observed for non-tactile measurement systems. The reason for that could be the rough nature of the FDM manufactured part but also evaluation and reporting errors occur as a result of intermediate steps carried out in non-tactile measurement such as fitting.

It is clear from Table 5 and Table 7 that measurement results of the parts taken by three different systems varied from each other for some of the dimensional features. These variations, which have different values for angular, linear and radial dimensions, were recorded at the highest rate in measuring angular dimensions while they were lowest in linear dimension measurements.

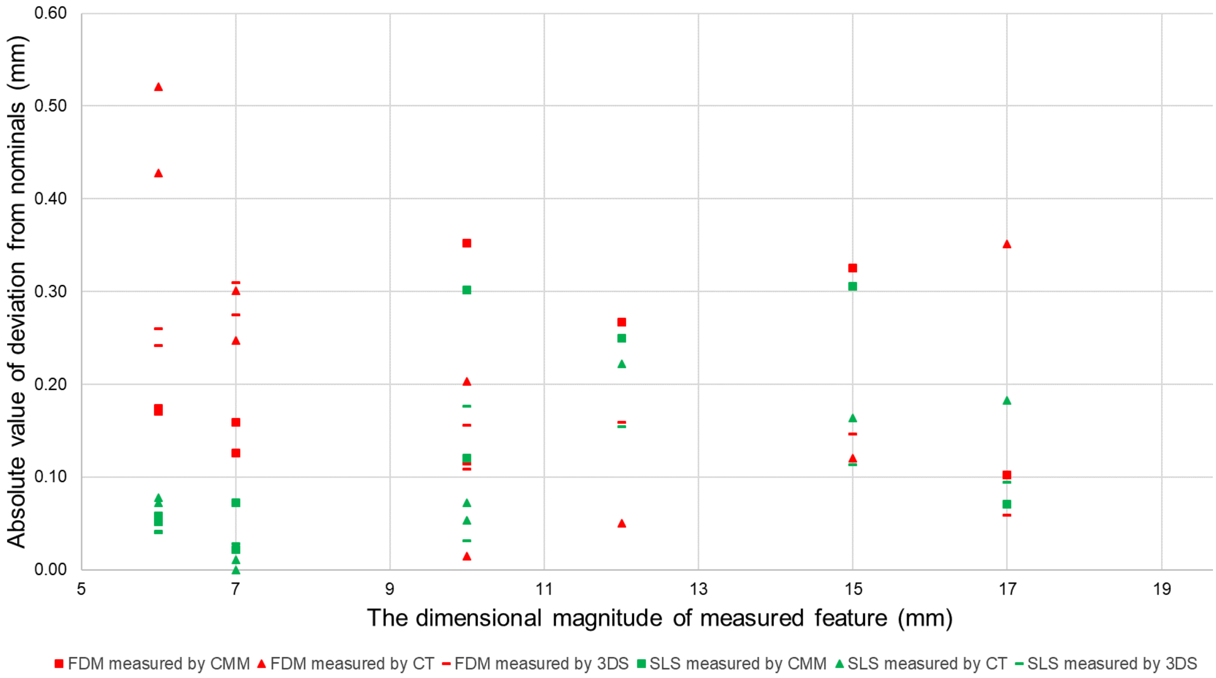

Figure 6. Benchmarking of manufacturing and measurement systems.

Table 7. CT and 3DS measurement results in mm.

Dimension	3DS		X-Ray CT	
	FDM	SLS	FDM	SLS
Angular Dim.1 (°)	60.09	61.123	60.465	61.223
Angular Dim.2 (°)	60.14	61.405	59.574	60.484
Linear Dim.5 (mm)	14.97	15.001	15.013	14.988
Linear Dim.6 (mm)	39.89	39.947	39.867	39.920
Linear Dim.7 (mm)	44.86	44.919	44.816	44.878
Linear Dim.8 (mm)	9.84	9.969	9.797	9.928
Linear Dim.10 (mm)	16.941	17.094	16.649	17.383
Radial Dim.1 (mm)	9.841	9.846	10.051	9.778
Radial Dim.2 (mm)	9.892	9.823	10.015	9.947
Radial Dim.3 (mm)	14.854	15.313	14.880	15.364
Radial Dim.4 (mm)	6.725	6.972	6.699	7.011
Radial Dim.5 (mm)	6.690	6.981	6.753	7.000
Radial Dim.6 (mm)	5.758	5.960	5.572	5.928
Radial Dim.7 (mm)	5.740	5.958	5.479	5.922

Variations between radial dimensions were also different for each measurement system. For instance, deviation of the FDM part angular dimension 2 from its nominal value recorded as 0.140 mm by optical scan while it was recorded as -0.426 mm and -0.695 mm for XCT and CMM respectively. Similarly, for SLS part angular dimension 2, the deviation was recorded as 1.205 mm, 0.484 mm and 1.815 mm for optical scan, XCT and CMM respectively. These deviations may arouse by different measurement procedures, algorithms and measurement parameters such as probe diameter for CMM [26], voxel size, voltage, current, filter materials and its thickness for XCT. [14] Collecting the measured point data from insides, diameter of the holes and inclined geometries is more difficult than simple linear geometries. Therefore, measurement errors and deviations can be seen at a higher rate in these regions. Also, the variability is more pronounced in FDM parts. This may be as a result of relatively higher surface texture irregularities and roughness.

Although, providing generation of 3D complex geometries, AM techniques also bring some challenges at the point of metrological evaluation of parts with these geometries. For dealing with these challenges measurement procedures have to be developed for AM parts manufactured with different materials by different AM methods.

The focus of this study was comparison of three most widely used precision metrology system in terms of dimensional inspection of polymer AM parts. Further analyses are needed by different measurement system parameters on different AM parts to develop measurement procedures and standards.

4. CONCLUSIONS

This study presented a benchmark for two polymer additive manufacturing technologies and their metrological evaluation using three different measurement systems of CMM, CT and 3DS using a special test artifact. As can be seen through the items listed below, the study revealed the superiorities and shortcomings of dimensional measurement systems relative to each other in products fabricated by polymer additive manufacturing. It can be concluded that;

- The benchmark highlighted the difference between part characteristics manufactured by FDM and SLS, where FDM part represented higher surface roughness and more deviation to the nominal design.
- Expanded uncertainties computed for the FDM manufactured part were almost three times of the uncertainties computed for the SLS manufactured part. It was also demonstrated that one of the major contributors to the expanded uncertainty occurred because of rougher surface of FDM manufactured part.
- In general consideration, similar tendency of part to nominal deviations were observable in all metrology systems including CMM, CT and 3DS. However, values of these deviations were in different ranges which revealed the need of standardized measurement and evaluation procedures for inspection and control of AM parts.
- Further comparative studies with different measurement system parameters, on different AM methods and materials would be valuable to development of required inspection procedures.

ACKNOWLEDGES

CMM and CT measurements were carried out at the Laboratory of Industrial Metrology and Adaptronic Systems, TU Wien (Vienna University of Technology), Austria. 3DS measurements were taken at Mayis Tasarim-Turkey. The authors would like to thank for all the supports.

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