Process Optimization: Internal Feature Measurement for Additive-Manufacturing Parts using X-Ray Computed Tomography

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ABSTRACT

X-ray computed tomography (CT) is a non-destructive approach to verify internal features of various industrial components built by additive manufacturing (AM) or other processing methods. However, the measurement results was highly impacted by numerous factors. In this study, DoE (Design of Experiments) was conducted to statistically study impacts of error source of X-ray CT metrology; optimal settings were recommended for different internal geometrical features. Measurement comparison between X-ray CT and CMM (Coordinate Measuring Machine) is also provided in this paper to analyze the principle difference of these two measurement technology.

Keywords: X-ray CT, internal features, AM (Additive Manufacturing), DoE (Design of Experiments)

1. INTRODUCTION

Additive Manufacturing (AM), or known as 3D printing, is a new technology that builds 3D objects by adding layer-upon-layer of material. Compared with conventional subtractive machining, the benefit of AM is the huge freedom to design and build complex internal geometrical features[1]. To verify these internal features, X-ray computed tomography (CT) is a promising technology and receiving increasing interests, due to its advantage in non-destructive evaluation on features at hard-to-contact locations[2]. However, the accepted standard of CT metrology is still under investigation: measurement accuracy is affected by numerous factors; internal geometry and irregular surface pattern of AM parts also make it challenging. CMM is a commonly used technology for high-accuracy dimensional measurement and can be used as a benchmark. However, small internal features with high roughness built by AM process may also bring in measurement uncertainties to tactile CMM system.

This paper presents a Design-of-Experiment (DoE)-based method to optimize operational process of X-ray CT measuring AM internal features. Measurement deviation of X-ray CT and CMM is also analyzed.

2. STRATEGY OF EVALUATION

2.1 Equipment and sample preparation

In this study, the X-ray CT (Nikon XTH 225ST with maximum voltage of 225kV) was used to measure a set of artifacts. Design of the artifacts are provided in Table 1. A pair of specimen fabricated by Maraging steel (MS1) were prepared for this investigation. The two artifacts, fabricated through machining and AM respectively, were designed with same geometry: a step shaft with a central hole with the diameter of 1 mm.

In this study, the central hole was measured by both CMM and X-ray CT. A comparison study was conducted. Details are provided in following sections.

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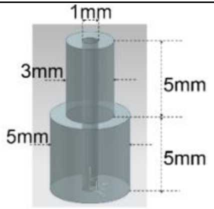
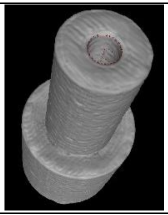
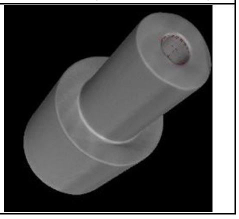
Table 1. A pair of specimen (step shaft, MS1 steel) was prepared for this investigation.

3D Drawing	AM	Machined	CT scan (AM)	CT scan (machined)
				

2.2 Design of experiments (DoE)

2.2.1 DoE Input

In this study, the input variables were the operational parameters of X-ray CT measurement.

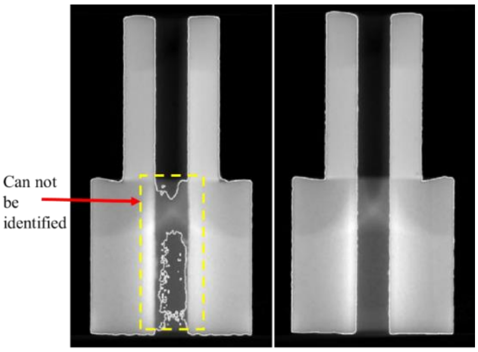
In principle, CT emits X-ray beams to penetrate objects and acquire cross-section images at certain magnification, by rotating objects to defined angle positions in one revolution[3]. The acquired images will be processed to reconstruct 3-dimensional (3D) structure, whose geometry can be measured providing a precise edge determination from air. Various factors of error source[1-6] are involved in equipment operation, specimen preparation, working environment and data processing, which will result in complex impact on X-ray CT's dimensional verification.

Table 2 shows the potential high-impact factors. 2-level factorial DoE was conducted using Minitab 17.

Table 2. The 2-level factors in DoE analysis.

	Factor	**Level 1**	**Level 2**
1	Surface roughness	AM specimen (high roughness): average Ra ~ 6.5 µm	Machining specimen (low roughness): average Ra ~ 0.4 µm
2	Wall thickness	Thin wall (top portion, wall thickness ~ 1mm)	Thick wall (bottom portion, wall thickness ~ 2mm)
3	Magnification	High (13.337); Voxel size ~ 15 µm	Low (6.666); Voxel size ~ 30 µm
4	Angular rotation steps	360 steps (1° per step)	>2000 steps (<0.18° per step)
5	Orientation of specimen placement	Without tilt	With tilt (~ 22 degree)
6	Filter application	150 kV without filter	215 kV with 0.5-mm copper filter
7	Eccentricity (specimen position during scanning)	Center of the rotation stage	10 mm offset
8	Surface determination	ISO 50%-50% rule[3]	Material 80% - background 20% (recommended for steel specimen)[3]

Factor 8, surface determination is a key setting for 3D reconstruction, which identifies the threshold to differentiate specimen material with air. 50%-50% rule is recommended as default setting. However, for high density material with high accumulated thickness, where image contrast could be relatively lower, 50%-50% rule may not be able to successfully determine the surface, as shown in Figure 1 (left). In order to correctly identify the surface, 80%-20% setting is recommended for steel specimen, as shown in Figure 1 (right).



ISO 50%-50% Rule 80%-20% Rule

Figure 1. Surface determination with 50%-50% and 80%-20% settings

Therefore, the DoE analysis in this study was separated into two sets:

DoE1 - Testing with 80%-20% setting only, when the system was able to differentiate the steel with the air for both thin and thick walls, 7 factors were studied: surface roughness, wall thickness, magnification, angular rotation steps, orientation of specimen placement, filter application and eccentricity.

DoE2 - Testing with thin wall only, when the system was able to differentiate the steel with the air with both 50%-50% and 80%-20% settings, 7 factors were studied: surface roughness, magnification, angular rotation steps, orientation of specimen placement, filter application, eccentricity and surface determination.

2.2.2 DoE Response

In order to evaluate the effects of the above input parameters, measurement deviation between X-ray CT and CMM was taken as the output of DoE. By statistically analyzing the dependency between the measurement deviation (DoE Response) and the operational parameters (DoE input), the key factors affecting measurement results can be determined.

For both CMM and X-ray CT measurements, diameters of 10 locations in the central hole were measured, and measurement deviations were calculated based on same location measurements.

3. RESULTS AND DISCUSSION

3.1 DoE 1

3.1.1 DoE 1 Results

For DoE 1, the setting of surface determination was chosen as 80%-20% rule (80% towards material and 20% towards background). The deviation between CMM and CT measurements ($|\mathrm{CT}-\mathrm{CMM}|$) was taken as the DoE response. The effects of different factors are shown in Figure 2.

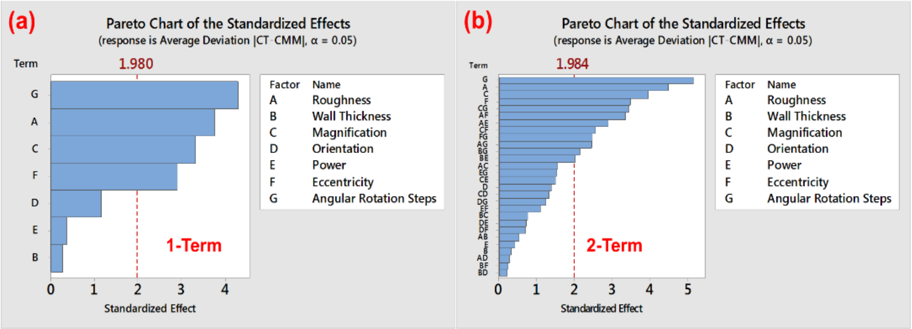


Figure 2. Pareto charts of average deviation on diameters measured (DoE 1: |CT-CMM|): (a) 1-term and (b) 2-term.

3.1.2 DoE1 Discussion

As demonstrated in Figure 2(a) and (b), four factors (angular rotation steps, roughness, magnification and eccentricity) were observed with top impact in both 1-term and 2-term analysis. Findings of DoE1 can be summarized as below:

- Angular rotation steps: High angular resolution helps to achieve high measurement accuracy.
- Eccentricity: Central placement helps to achieve high measurement accuracy.
- Magnification: Although high magnification increases the voxel resolution, measurement accuracy might be affected due to edge blurring[7-8].
- Roughness: Although surface roughness has very high impact on measurement deviation ($|\mathrm{CT} - \mathrm{CMM}|$), it's risky to conclude that high roughness leads to low accuracy. Because for rough surfaces built by AM process, surface texture is a part of geometry and tactile probes of CMM may not be able to accurately express the geometry. Detailed discussion will be provided in Section 4.

3.2 DoE 2

As indicated in Section 2.2, DoE 2 focused on thin-wall geometry only, but extended the evaluation on setting of surface determination: ISO 50%-50% rule or 80%-20% rule recommended for steel specimen. The respective analysis on response of average deviation (|CT-CMM|) was demonstrated in Figure 3.

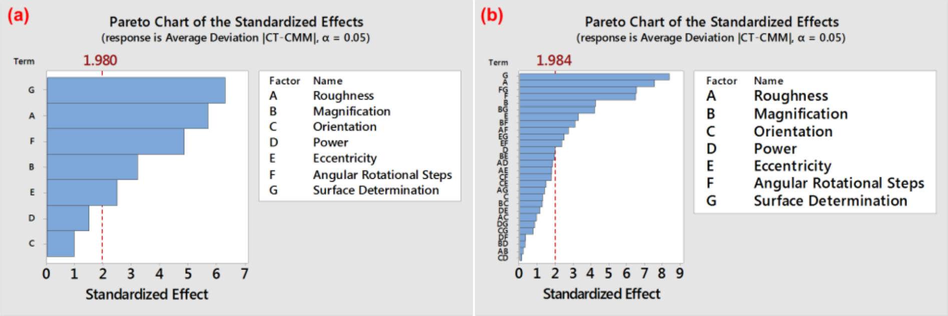


Figure 3. Pareto charts of average deviation on diameters measured (DoE 2: |CT-CMM|): (a) 1-term and (b) 2-term.

3.2.1 DoE2 Discussion

As demonstrated in Figure 3(a) and (b), Findings of DoE2 can be summarized as below:

- Similar with DoE1, magnification, eccentricity and angular rotational steps are key factors affecting measurement results.
- Surface determination impactful affects X-ray CT measurement results.
- 2-term analysis results show that compound effects FG (angular rotational steps and surface determination) and BG (magnification and surface determination) also significantly affect measurement results

Figure 4 shows the effect of surface determination. When 50%-50% setting was applied, background (air) and metal (steel) are clearly separated. For lower contrast images, when 80%-20% setting was applied, the threshold (red line) may also exclude some metal, which leads to a positive measurement error for hollow feature measurement.

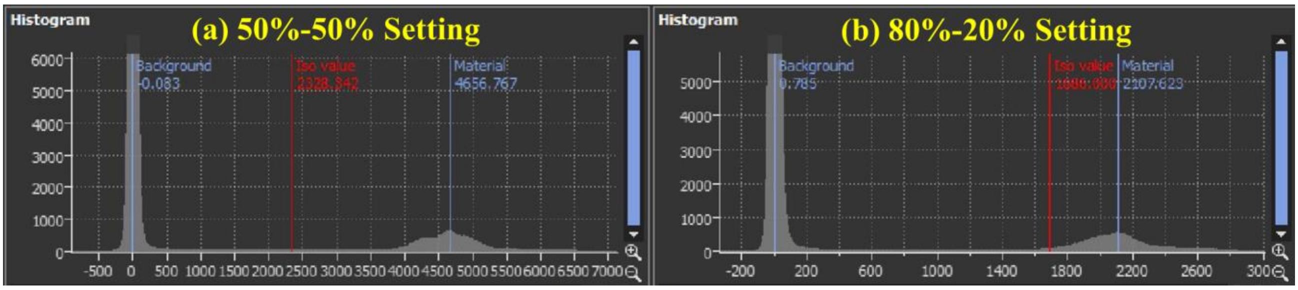


Figure 4. Surface determination using different settings.

4. VALIDATION AND DISCUSSION

4.1 Validation

From DoE results shown in Section 3, using low maginifcation, high angular resolution and central placement may optimize the X-ray CT meaurement accuracy. For validation purpose, both AM and machined specimens were remeasured using this setting. 10 locations in the central holes were measured, with 10 repeats for each. For each location, both X-ray CT and CMM showed a standard deviation less than 2 µm. Average measurement deviations are shown in Table 3:

Table 3. Comparison on 10 circles' diameter (X-ray CT (recommended setting) and CMM) of each specimen

Wall thickness	**Location**	**Average deviation (CT-CMM) – Machined specimen (µm)**	**Average deviation (CT-CMM) – AM specimen (µm)**
1 mm (50%-50% setting)	1	-2.7	19.8
	2	-2.2	14.6
	3	-3.1	24.4
	4	-3.4	19.1
	5	-2.6	16.6
	Average	**-2.8**	**18.9**
2 mm (80%-20% setting)	6	-2.4	43.5
	7	-2.8	51.1
	8	-4.4	38.2
	9	-1.7	38.0
	10	-3.1	29.8
	Average	**-2.9**	**40.1**

4.2 Discussion

Measurement data of machined specimen shows that the deviations between CMM and X-ray CT are within 3 µm. For specimens with smooth surfaces, CMM measurement can be seen as the reference. Therefore it can be conclude that applying low maginifcation, high angular resolution and central placement will help X-ray CT to improve measurement accuracy.

For AM specimens with rough surfaces, it's challenging to use CMM to perform high-accuracy measurement. In this study, the tip ball size of the CMM stylus was 0.3 mm, the smallest size for most commercial CMMs. It's still too big to profile a rough surface. As shown in Figure 5, for a rough internal surface, CMM tends to acquire the inscribed curve. In contrast, X-ray CT tends to acquire the curve between peaks and valleys, which leads to a greater diameter value than the CMM measurement. The accessiblity limitation of CMM could explain the measurement deviation shown in Table 3: For the AM internal feature, X-ray CT measurement values are obviously greater than CMM results.

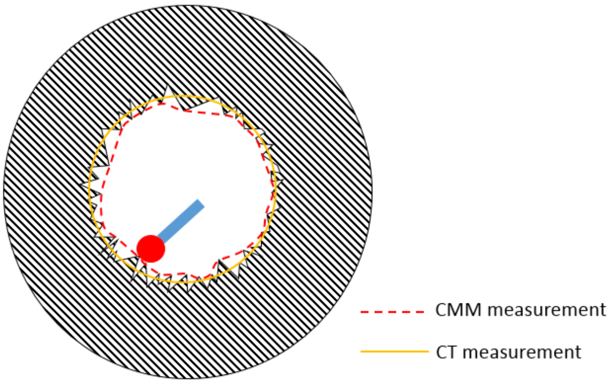


Figure 5. Profile determination for rough surfaces.

For thin wall portion of the AM specimen, the deviation is around 20 µm. For thick wall portion, when 80%-20% setting was applied for surface determination, the deviation is 40 µm. However, such different setting didn't make significant difference for machined specimen measurements (-2.8 µm vs -2.9 µm). Therefore it can be conclude for AM specimens with high surface roughness, surface determination method could be a key contributor to measurement uncertainty, due to the low surface integrity.

In summary, this paper presents a DoE-based method to analyze the key factors that affect X-ray CT measurement. DoE results showed that magnification, angular resolution, sample placement offset and surface determination method significantly affect the measurement results. Rough surfaces built by AM process also brings new challenges for both X-ray CT and conventional tactile CMM. Further study is needed to standardize the definition of the geometries with high roughness and irregular surface textures.

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