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Measurement of Additively Manufactured Internal Surface Structure Using an X-ray Computed Tomography

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The measurement of external surface topography including regular and random rough surface structures fabricated by conventional machining process has been well developed. However, it is impossible for those methods based on the stylus or optical profilometry to conduct measurements of internal structuresfabricated by additive manufacturing (AM) process since the related stylus/optical probe cannot access internally hidden areas of interest. Advanced X-ray computed tomography (XCT) offering micro-scale resolution can do it as X-ray can penetrate the materials and then pick up the hidden surface information.In this study, we prepared internal surface structures present in additively manufactured parts and successfully conducted measurementsusing an advanced high-resolution XCT. To quantitively demonstrate XCT feasibility for measuring internal surface structures, both conventional turned part and AM part assembled to be internal surfaces were measured by the XCT. The XCT 3D surface topography measured shows clear images of the internal structure with 4 flat surface step heights of Type A1 (ISO5436-1) ranging from 30 µm to 250 µm on the internal surface of the turned part and varied areal surface roughness values of Sa (ISO 25178-2) ranging from 4 µm to 20 µm on AM internal surfaces. Corresponding XCT measured results are favorably comparable to those reference values obtained by a traceable laser confocal microscope. It successfully demonstrated that the proposed XCT methodology is non-destructively and quantitively capable of providing micro-scale surface topography data comparable with conventional surface measurement technologies. In addition, the designed parts can be used as testing coupons for verifying the XCT measurement accuracy of the AM fabricated internal structure.

1. Introduction

Additive manufacturing (AM) [1]as one of important technologies in advanced manufacturing and engineering is widely adopted by diverse industrial sectors, such as aerospace, oil & gas, precision engineering, MedTech etc. Since AM has an inherent & unique layer-by-layer process to produce parts based on CAD models, it is capable of fabricating parts with complex geometrical internal structures, which is impossible to be done by conventional manufacturing technologies, such as lapping, turning, milling, casting and etc. Compared to those conventional subtractive manufacturing, however, AM's layer-by-layer process gives also challenges and barriers for those complex components to be properly measured by applying quality control for AM printed internal or hidden dimensional and surface geometrical inspection and verification. Surface internal structure/roughness is one of critical performance parameters that requires quality control in product manufacturing, especially when AM is widely applied in industry to fabricate complex geometry and internal structure with a high-aspect ratio. So far, there is a gap of no proper measurement method (e.g., lack of measurement accuracy & traceability) to conduct related internal surface structure and roughness measurement onto those high-aspect ratio internal surfaces.The surfacestructure of external AM surface can be determined by the mechanical stylus/optical probe profilometry[2-4]. However, those techniques have limitations to allow the mechanical stylus & optical probes contacting with those internal surface structures.X-ray computed tomography (XCT) allows the acquisition of AM part's internal and external geometries at high dense sampling points to detect and measure those hidden structures based on X-ray penetration through AM parts materials and subsequent CT images can carry dimensional information of those internal structures.

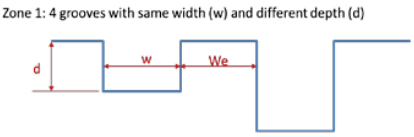
Thisstudy aims to conduct a feasibility study of AM's internal surface structure measurement using XCT. It is intended to explore a high-resolution XCT for a traceable internal surfaced structure/ roughness measurement. To do so, a comparison measurement of designed and fabricated samples with internal surface structures is conducted to demonstrate XCT measurement accuracy by comparing results obtained by a traceable laser confocal microscope [5].

2. Methodology

2.1 Preparation of Samples

As shown in Fig. 1(a), one sample with an internal cavity was formed by two separate parts (maraging steel) fabricated by a tuning machine.

(a)



Zone	d (mm)	w (mm)	We (mm)
1	0.03	1	1~2
	0.05	1	1~2
	0.10	1	1~2
	0.25	1	1~2

(b)

Fig. 1 (a) Photo of a tuned surface sample with 4 different step heights on the surface of the formed internal cavity and (b) Schematic of the flat step height with nominal depth (d) values of (30, 50, 100 and 250) µm.

Another sample (maraging steel) fabricated by AM - selective laser melting (SLM) process was designed as a box with 3 covers building direction along 0°, 45° and 90° in SLM process, which is intended to simulate surface roughness on different slanted surfaces built along 3 directions for demonstrating surface quality differences due to a change of AM building directions. In this case, hidden/internal surfaces are prepared as a testing coupon in the following experiments.

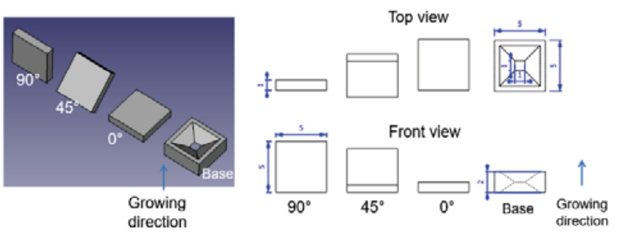


Fig. 2 Design of an AM sample with 3 plates building in 0°, 45° and 90° to cover the top of Base part for forming a box (5 mm ×5 mm × 3 mm).

2.2 Experiment

To obtain reference data of those internal surface step height and surface roughness information, a standard laser confocal microscope is applied to measure surface structures before related parts are assembled to be an internal cavity and a Box. The laser confocal microscope (resolution: 0.02 µm) has been calibrated at NMC with a high accuracy traceable to SI unit of metre definition. After the separate parts are assembled to be the cavity and the box, corresponding hidden & internal structures are evaluated by the proposed XCT to study how good XCT can conduct the measurement of those hidden surface structures.

2.3 Data Process

Since XCT can obtain all 3D voxel data of the sample as X-ray

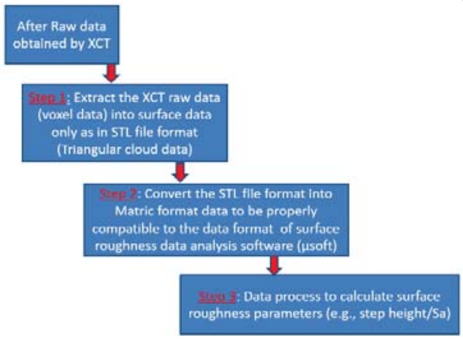


Fig. 3 A flow chart of a procedure to process XCT data through a standard surface metrology program for calculating step height and surface roughness.

going through 3D samples. However, those surface structures are only data of the boundary surface from solid sample materials to the air. It is necessary to just abstract the boundary surface information. In this case, Fig. 3 shows the data process procedure.

3. Results and Discussion

Fig. 4 and Fig. 5show a 3D plot obtained by the proposed XCT (Voxel size: 5 µm; 150KV/120µA; 0.5 mm Cu Filter). It shows those step heightstructures are clearly identified.

Fig. 4 3D plot of step height structure (four steps: 250 µm, 100 µm, 50 µm and 30 µm) acquired by XCT.

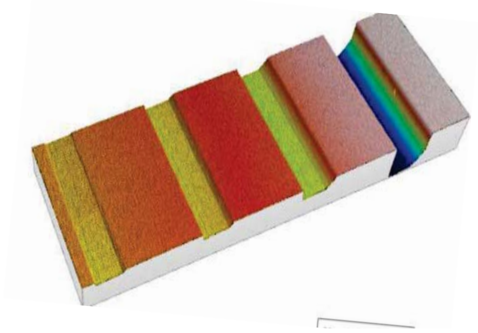


Fig. 5 3D plot of the four steps after removed the global curvature.

As an example, a 2D plot of mean step height result (nominal step

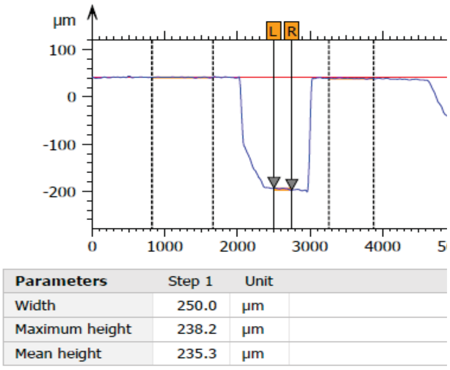


Fig. 6 2D plot of the step height structure with a step height determined by XCT as 235.3 µm.

height250 µm) is shown in Fig. 6. It can be seen that the actual mean step height is 235.3 µm measured by XCTper ISO 5436-1 [6].

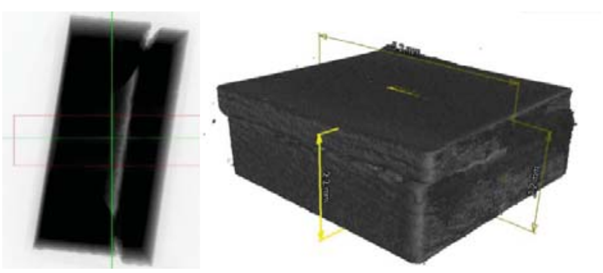
The sample with fourstep heightsis measured by both laser confocal microscope and XCT respectively. In Table 1, the fourstep heights from 2 different measurement methods are summarized. The

Table 1. Summarized results of four step heights (Unit: µm).

Step Height by Confocal	U95	Step Height by XCT	2σ	Deviation
12.77	0.28	12.58	0.23	-0.18
39.22	0.62	39.15	0.55	-0.07
79.55	1.22	79.65	0.86	0.10
235.27	3.47	235.37	0.55	0.10

measured results (Deviation) are in an order of 0.1 µm. Therefore, XCT measurement results are comparable to those obtained by reference measurement results using the laser confocal microscope. In addition, it is noted that the standard deviation (2σ) from XCT results could indicate the step height uniformity and be used in XCT measurement uncertainty evaluation.It is noted that the laser confocal microscope has a measuring resolution of 0.02 µm much better than the 5 µm voxel size resolution in XCT. Also considering there are a number of uncertain source of errors (e.g., beam hardening & X-ray defects affecting surface isolation from physical part edge to the surrounding air boundary and etc.) in XCT, actual XCT step height measurement accuracy needs to be further studied in the further work.

Fig. 7 shows the AM fabricated box sample XCT results. It is seen
that internal surface structures can be clearly observed by the proposed XCT.



(a) (b)

Fig. 7 AM sample measured by XCT: (a) A typical 2D X-ray projection image during XCT scanningand (b) 3D plot of AM box sample measured by XCT.

Based on raw surface topography data captured by XCT from those different printing build directions, the areal surface roughness calculation can be defined as a surface roughness (Sa - arithmetical mean height)per ISO 25178 [7]. Fig. 8 shows XCT results of AM

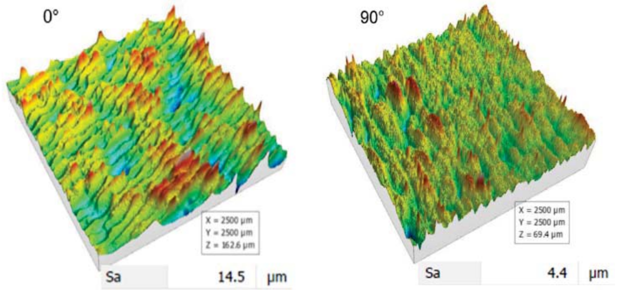


Fig. 8 3D plot of XCT results of AM fabricated surface along 0°and 90° building directions respectively.

internal surfaces hidden in the assembled box. It is seen that the surface along 90° building direction has less Sa(4.4 µm) than the surface of Sa (14.5 µm) built in SLM along 0° printing direction.It demonstrates that surface quality in SLM process along 90° building direction is better than the surface along 0° building direction. In Fig. 8, the printing hatch sign and laser scanning direction in the melted surfaces can also be observed.

Similarly, Fig 9 shows that the surface along 45° lower surface has a larger Sa (16.5 µm) than 45° upper surface of Sa (10.3 µm). This is expected as the 45° lower surface with no supporting structure

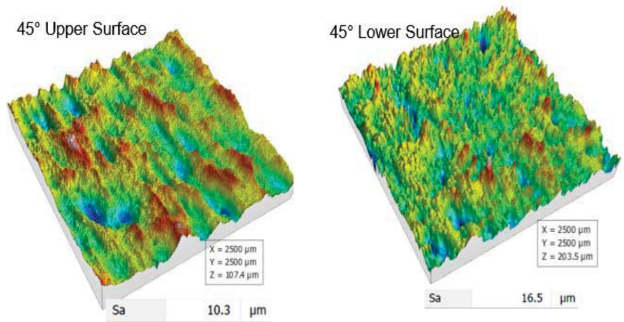
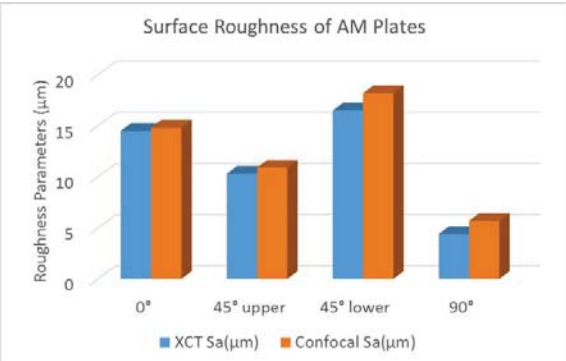


Fig. 9 3D plot of XCT results of AM fabricated surface along 45°upper and lower surfaces respectively.

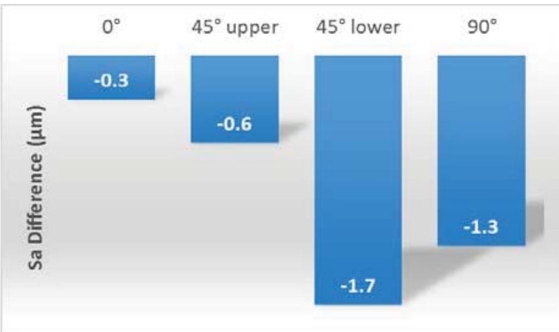
during AM process and those melting powder is dropped downdue to gravity force, which introduced larger height variation in this 45° lower surface. It is noted that the hatch sign and the laser scanning direction of 45° lower surface are less obvious than those in 45°upper surface, which could also indicate the melting pool has not been controlled or not properly constrained around the laser spot region as the melting powder running more randomly. This is because no supporting surface's qualityis significantly affected by the gravity force effects. Overall, it is found that Sa values are as follows: 90° < 45° upper < 0° < 45° lower. The vertical surface (90° building direction in SLM) has a smaller surface roughness,and the 45°lower surface has the largest surface roughness.

To verify measurement accuracy of surface roughness of those hidden surfaces by the proposed XCT as described above. Those separate AM fabricated surfaces have been also measured by laser confocal microscope. Measured results of areal surface roughness Sa are determined and compared to XCT results of the same sample and the same area of interests on each surface (0°, 90° and 45° upper & lower surfaces). The comparison results are shown in Fig. 10.

It is worth noting that Sa surface roughness parameter measured



(a)



(b)

Fig. 10 (a) Overall comparison results between XCT and laser confocal microscope and (b) Corresponding surface roughness difference between laser confocal microscope and XCT.

by XCT is always smaller than surface roughness parametersof four samples measured by laser confocal microscope. This is mainly because the laser confocal microscope has a much better vertical resolution (0.02 µm) and lateral resolution (1 µm: laser spot diameter on the testing surface) than the XCT resolution (5 µm voxel size) in 3D. Therefore, the laser confocal microscope can collect more detailed 3D surface topography information.

4. Conclusions

Internal surface structures consisting of substrative tuning process and AM samples are designed and fabricated respectively as the testing coupon to study the feasibility and accuracy of the internal structure measured by XCT. The internal surface structures including step height and surface roughness have been evaluated by XCT and a standard laser confocal microscope. The related internal structure measurement performance by XCT (Voxel size: 5 µm) has been verified by the comparison with measurementsof the laser confocal microscope (vertical resolution: 0.02 µm and lateral resolution: 2 µm). Corresponding step height and areal surface roughness (Sa) measured by XCT are deviated in the order of sub-micrometers and micrometers, respectively from the standard laser confocal microscope. The results demonstrated that the step heights and amplitude surface roughness parameters of the surface topography by the proposed XCT are comparable to the measurements by the laser confocal microscope. XCT can be an important complemented tool in AM metrology development.

REFERENCES

[1] Gibson I, RosenDand Stucker B 2010 Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing (New York: Springer).

[2] Triantaphyllou A, Giusca CL, Macaulay GD, Roerig F, Hoebel M, Leach RK, et al. Surface texture measurement for additive manufacturing. Surf Topogr:Metrol Prop, 2015;3:024002.

[3] Mumtaz K, Hopkinson N. Top surface and side roughness of Inconel 625parts processed using selective laser melting. Rapid Prototyp J, 2009;15:96–103.

[4] Grimm T, Wior G, Witt G. Characterization of typical surface effects inadditive manufacturing with confocal microscopy. Surf Topogr: Metrol Prop2015; 3:014001.

[5]Wang Shihuaand Yu Shengkai, "Micro-scale surface metrology using a large scanning rangenon-contact laser confocal microscope", Proceedings/SPIE, Vol.11552, 1155204-1 to1155204-10, Oct 2020.

[6] ISO 5436-1:2000, Geometrical Product Specifications (GPS) - Surface texture: Profile method; Measurement standards.

[7] ISO 25178: Geometrical Product Specifications (GPS) – Surface texture.