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Full Length Article

Internal surface measurement of metal powder bed fusion parts

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ABSTRACT

Recent advances in X-ray computed tomography (XCT) have allowed for measurement resolutions approaching the point where XCT can be used for measuring surface topography. These advances make XCT appealing for measuring hard-to-reach or internal surfaces, such as those often present in additively manufactured parts. To demonstrate the feasibility and potential of XCT for topography measurement, topography datasets obtained using two XCT systems are compared to those acquired using coherence scanning interferometry and focus variation microscopy. A hollow Ti6Al4V part produced by laser powder bed fusion is used as a measurement artefact. The artefact comprises two component halves that can be separated to expose the internal surfaces. Measured surface datasets are accurately aligned and similarly cropped, and compared by various qualitative and quantitative means, including the computation of ISO 25178-2 areal surface texture parameters, commonly used in part quality assessment. Results show that XCT can non-destructively provide surface information comparable with more conventional surface measurement technologies, thus representing a viable alternative to more conventional measurement, particularly appealing for hard-to-reach and internal surfaces.

1. Introduction

Additive manufacturing (AM) technologies have the ability to produce parts containing complex geometries that were previously impossible to manufacture by conventional means [1]. A number of barriers to increased adoption of AM parts exist, however, relating to the difficulties in applying quality assurance principles, such as dimensional and geometric inspection and verification [2]. In particular, when inspecting AM surfaces, conventional optical and contact surface measurement solutions are often incapable of measuring the inaccessible and internal surfaces. Such conditions are common with typical AM geometries, such as hollow parts and lattice structures [3–5].

X-ray computed tomography (XCT) has recently become established as a useful tool in holistic measurement of industrial parts, and is steadily being incorporated into the metrological toolbox [6]. Although much work remains in standardisation of the use of XCT for metrology (ISO 10360-11 [7] is still in the draft stages), XCT has begun to show promise for the verification of internal geometries present in AM parts [8]. Although the spatial resolutions typically achievable by XCT have not historically been at the level required to capture the smaller-scale formations of a surface in addition to the overall shape, advanced systems are approaching these resolutions in their best-case measurement scenarios, and so XCT is becoming an viable option for measurement of surface topography. When considering the fact that AM parts commonly feature complex, internal geometries, the prospect of using XCT for surface topography measurement appeals further, as a method of overcoming the access requirement problems intrinsic to contact and optical measurements. The use of XCT for surface topography measurement is highlighted in a number of recent studies [9–14]. Specifically, Pyka et al. [9,10] performed the first surface topography measurement using XCT, by extracting profiles from slice data obtained from XCT measurement of lattice struts. Townsend et al. [12,13,15] and Thompson et al. [14] extended this work by initiating a more extensive examination of XCT topography measurement performance in comparison to conventional optical surface measurements, with the most recent work by Townsend et al. [13] examining the output of a number of measurements performed across several laboratories. Much work exists in the validation of XCT for internal topography measurement. However, to date and to the authors' knowledge, no research effort has been specifically dedicated to investigating the challenges of measuring topography of internal surfaces. To address this research need, an investigation comparing internal XCT surface measurements and measurements made using conventional optical surface technologies is presented in this paper.

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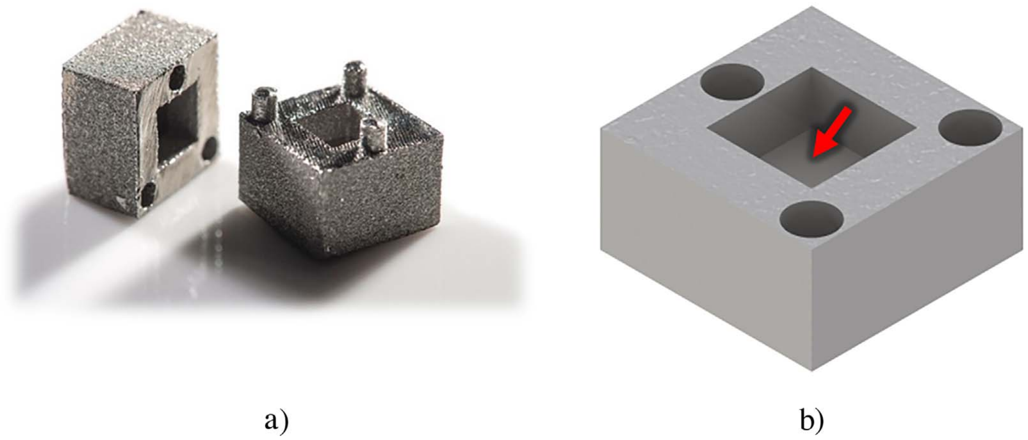

Fig. 1. a) Artefact for the measurement of internal surface texture. When assembled, cube dimensions are (10 × 10 × 10) mm; b) The surface of interest, indicated by the arrow on a CAD rendering of one half of the artefact.

2. Methods

A metal laser powder bed fusion (LPBF) hollow artefact was measured using two commercial XCT systems (labelled “XCT 1” and “XCT 2” respectively), as well as by two non-contact optical measurement systems. Measurements were performed using input parameters optimised for each system based upon the manufacturer’s recommendations and the authors’ prior experience, but all instrument names have been redacted from this publication to prevent undue comparison of commercial instruments. The artefact used in this work was produced in two separable parts (see Fig. 1) from Ti6Al4V using an EOSINT M 280 metal LPBF machine. The manufacturer’s proprietary process parameters for Ti6Al4V were used to produce the artefact. Ti6Al4V was chosen as the artefact material for its suitability to XCT measurement [8] and general industrial relevance. When assembled, the artefact simulates the metrological challenge of internal geometries as surfaces become inaccessible to conventional optical surface measurement solutions. When separated, surfaces can be inspected using optical technologies.

2.1. *XCT measurements of surface topography*

XCT 1 measurement setup: voltage 150 kV, current 36 µA, 3142 projections formed from averaging two images per projection, each using an exposure of 2829 ms, geometric magnification 35 × yielding a voxel size of 5.7 µm after reconstruction. A warmup scan of approximately one hour was performed prior to the scan and a 0.25 mm copper pre-filter was used between the X-ray source and the specimen. X-ray imaging and volumetric reconstruction were performed using manufacturer’s proprietary software, using filtered back projection with a beam hardening correction and a Hanning noise filter [16].

XCT 2 measurement setup: voltage 160 kV, current 63 µA, 1600 projections formed from one image per projection, each using an exposure of 6000 ms, geometric magnification of 5.75× and optical magnification of 0.4× yielding a voxel size of 5 µm after reconstruction. A proprietary pre-filter was used according to the manufacturer’s guidelines. X-ray imaging and volumetric reconstruction were performed using the manufacturer’s proprietary software using filtered back projection with a beam hardening correction and a Gaussian reconstruction filter with a kernel size of 1.

Reconstructed volumetric data were imported into VolumeGraphics VGStudioMAX 3.0 [17] and surfaces were determined using the iterative maximum gradient method over four voxels, using the ISO-50 isosurface as a starting point (see Fig. 2a) [18].

2.2. *Optical measurements of surface topography*

Coherence scanning interferometry (CSI) measurement setup (where LR is lateral resolution and FoV is field of view): 20 × objective lens at 1 × zoom (NA 0.40, FoV 0.42 mm × 0.42 mm, LR-pixel 0.41 µm, LR-optical 0.68 µm). Stitching of multiple FoVs was performed using the manufacturer’s proprietary software. Vertical stitching was also applied, to merge two measurement z intervals (145 µm and 100 µm wide respectively, with 10 µm overlap). LR-pixel refers to the pixel width of the detector used by each instrument, while LR-optical refers the calculated optical Sparrow limit of each instrument.

Focus variation (FV) measurement setup: 20 × objective lens (NA 0.40, FoV 0.81 mm × 0.81 mm, LR-pixel 0.44 µm, LR-optical 0.68 µm) was used with ring light illumination. Vertical resolution was set at 50 nm and LR-contrast at 3 µm, where LR-contrast refers specifically to the distance from the centre of each pixel used by the FV instrument to compute local contrast; selected during the measurement. Stitching of multiple fields of view was performed in the manufacturers’ proprietary software.

2.3. *Data processing*

XCT surface data were cropped to extract the surface of interest in VGStudioMAX, and exported as triangulated meshes in .stl format. Triangulated meshes were rotated in MeshLab [19] to align the surface normal to the z axis (surface normal computed via principal component analysis [20] on the mesh point cloud), and exported again as an .stl. The rotated mesh was then imported into the surface metrology software MountainsMap [21] and resampled into height maps at a resolution automatically determined by MountainsMap to match the point density of the triangulated mesh (see Fig. 2b).

Height maps obtained by XCT and optical measurement were relocated in the same coordinate system using MountainsMap by application of a marker-based coarse alignment, followed by cross-correlation based global algorithmic alignment [22]. From the aligned height maps, regions of size (1.5 × 1.5) mm were extracted, and levelled by least-squares mean plane subtraction, allowing like-for-like comparison of surface data. This sample size was chosen as, at 20 × magnification, measurement of a larger area by CSI was deemed unfeasible due to the prohibitive number of stitching operations, and measurement times. Topography datasets were bandwidth-matched [23] (involving the application of filtering operations with identical cut-off wavelengths across datasets) to allow comparison of the resulting parameters. Extracted surfaces were initially filtered using a Gaussian convolution S-filter with a 13 µm cut-off to remove small-scale surface features; chosen as the minimum possible for the lowest lateral resolution height map (XCT 2), representative of a grid of 4 × 4 pixels. A Gaussian convolution L-filter with a 1.5 mm cut-off was then chosen as equal to the size of the region of interest. This operator was applied to remove tilt and waviness at scales larger than the field of view, therefore obtaining SF surfaces. A Gaussian convolution L-filter with a 0.5 mm cut-