Precision Engineering 53 (2018) 54–64

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Effects of magnification and sampling resolution in X-ray computed tomography for the measurement of additively manufactured metal surfaces[☆]

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ARTICLE INFO

Keywords:
X-ray computed tomography
Metrology
Surface texture
Metal powder bed fusion

ABSTRACT

Recent studies have shown that X-ray computed tomography (XCT) can be used to measure the surface topography of additively manufactured parts. However, further research is necessary to fully understand XCT measurement performance. Here, we show how magnification of the X-ray projections and resolution of the volumetric reconstruction grid influence the determination of surface topography in the XCT data processing pipeline. We also compare XCT results to coherence scanning interferometry (CSI) measurements and find that by increasing the magnification of the X-ray projections, smaller topographic detail can be resolved, approaching the lateral resolution of CSI. Results show that there is an optimum setting for magnification, below and above which XCT measurement performance can degrade. The resolution of the volumetric reconstruction grid has a less pronounced effect, but in general, adopting higher or lower resolutions than the default leads to degraded repeatability in surface determination. The problem of determining sensitivity of XCT surface measurement as a function of setup parameters is complex, and it is not yet possible to provide optimal setup configurations that work regardless of object geometry. However, the methods presented here, as well as the results obtained, represent a useful contribution to good practice for XCT measurement of surfaces.

1. Introduction

Additive manufacturing (AM) represents a new technique in the toolbox of production processes, in that the design freedom provided by AM enables the creation of parts that have not previously been possible using conventional subtractive manufacturing methods [1]. For example, many AM processes are capable of producing freeform hollow, trabecular or otherwise complex and topologically optimised parts, capable of significant mass saving in high-value applications, such as in the aerospace, automotive and biomedical sectors.

There are currently a number of substantial barriers to increased adoption of AM technologies. If a manufacturer wishes to place a part into a commercial aircraft, for example, rigorous verification standards must be met in order to ensure the sufficiency of that part's quality. However, when compared to parts produced by conventional means, additive manufacturers encounter issues relating to poor mechanical performance (for example, fatigue [2], creep [3]), limitations in the pool of available materials, and difficulty in verification of parts [4,5].

Existing part inspection and verification practices are well developed, and work well for conventionally manufactured parts, but AM parts commonly cause additional issues. Conventional verification methods involving co-ordinate measuring systems are often not possible [6], as the geometries commonly produced by AM processes contain features inaccessible to conventional measurement technologies. In particular, AM parts commonly contain function-critical surfaces that are inaccessible to both contact and optical measurement technologies [7].

To overcome the issues faced by contact and optical measurement technologies, X-ray computed tomography (XCT) has been increasingly recognised as a viable solution for dimensional measurements in AM [8]. Similarly to AM technologies, however, a relatively poor understanding of the XCT measurement process is one of the factors preventing more widespread adoption, and substantial work is required to qualify XCT as a reliable verification method [9]. Particularly, XCT has become recognised in a number of recent publications [7,10–15] as a viable method of surface topography measurement for

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[☆] This paper was recommended by Associate Editor Han Haitjema.
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https://doi.org/10.1016/j.precisioneng.2018.02.014
Received 27 November 2017; Received in revised form 23 February 2018; Accepted 28 February 2018

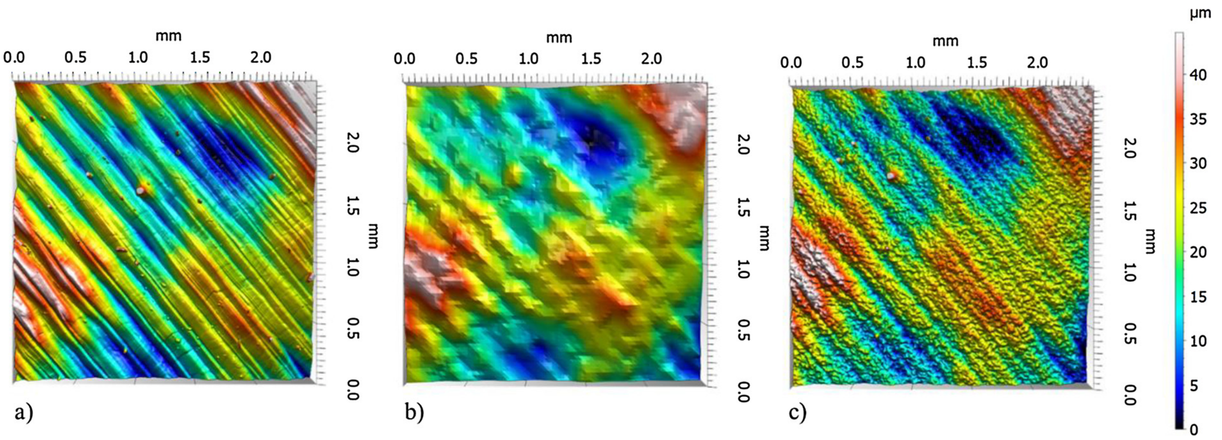

Fig. 1. Example topographies obtained by varying XCT measurement setup: a) CSI reference; b) XCT measurement using 5 × magnification; c) XCT measurement using 20× magnification.

internal and hard-to-reach surfaces. Pyka et al. [10,11] made the first XCT surface measurements, in which they extracted profiles from XCT orthoslices and computed ISO 4287 [16] texture parameters on these profiles. Thompson et al. [7,13,17] and Townsend et al. [14,15] later extracted areal topographies from XCT data and compared them to data acquired using state-of-the-art optical surface measurement technologies. Townsend et al. [14] compared XCT surface data to focus variation [18,19] measurements by examining ISO 25178-2 [20] areal texture field parameters. They examined how a number of factors affect XCT surface measurements [15], focusing on surface determination methods, XCT filament replacement and internal against external surface measurement. In recent work [13,17], we presented the results of a comprehensive effort involving the direct quantification of discrepancies between topographic reconstructions, covering XCT surface measurement in comparison to the major optical areal topography measurement technologies: confocal microscopy [21,22], coherence scanning interferometry (CSI) [23,24] and focus variation microscopy [18,19]. We also found during the aforementioned studies that the surface topographies produced by XCT measurement can be highly variable (see Fig. 1) depending on the setup of the measurement parameters in the instrument.

A comprehensive assessment of XCT performance and behaviour when measuring surface topography, as well as a thorough exploration of the effects of the numerous involved measurement process parameters, has yet to be performed. The challenge represented by this assessment is significant, because of the large number of variables involved in the initial acquisition of the X-ray projections, in their combination into a volumetric dataset, and in the final extraction of surface topography [7].

Here, we investigate the effects of changing two variables during the measurement process. The first of which is one of the most important parameters set during X-ray image acquisition: the magnification of the X-ray projections. Referred to as *magnification* in the following, this is the ratio between the X-ray source-to-detector distance and the X-ray source-to-object distance [25] (see Fig. 2a). The latter variable is one of the most important variables set during volumetric reconstruction: the resolution of the volumetric reconstruction grid [26] (see Fig. 2b); referred to hereafter as *resolution*. Both magnification and reconstruction affect the capability of the instrument to resolve small topographic detail in the extracted surface. For this experiment, we use a cone beam XCT system, circular scanning and a planar detector. Volumetric reconstruction is performed using the manufacturer's implementation of the Feldkamp, Davis and Kress (FDK) algorithm [27]. As such, our results reflect this general setup.

2. Methods

2.1. Sample

The test sample, developed to study internal surfaces in previous work [7], was comprised of two separable halves that could be combined to form a hollow cube of size (10 × 10 × 10) mm. The sample was fabricated using an EOSINT M 280 metal LPBF machine in Ti6Al4 V. The test surface chosen was a nominally flat top surface, i.e. the final surface built in the LPBF machine, in the plane orthogonal to the build direction. X-ray images (i.e. projections) were taken, at different magnifications (5×, 10×, 20× and 50×). Each set of projections was used for multiple volumetric reconstructions using resolutions: 50 %, 100 % and 150 %, where 100% corresponds to the resolution of the detector. For example, in the 20× magnification, 100 % resolution case, a detector containing a grid of 2000 × 2000 pixels of size (0.2 × 0.2) mm will yield a reconstructed volume containing 2000 × 2000 × 2000 voxels, each of size (10 × 10 × 10) µm. The 50 % and 150 % cases will then contain 1000 × 1000 × 1000 voxels, each of size (20 × 20 × 20) µm, and 3000 × 3000 × 3000 voxels, each of size (6.7 × 6.7 × 6.7) µm, respectively (see Fig. 2b). The 150% and 50% cases are examples of super-sampling and sub-sampling conditions, respectively.

2.2. Measurement setups

The sample was measured using a number of XCT measurement setups, as well as by CSI. In all measurement setups, five repeat measurements were taken in sequence, on the same instrument, with the same operator and without moving the sample between acquisitions.

XCT measurements were performed using a Nikon MCT 225, at geometric magnifications of 5×, 10×, 20× and 50×. The following parameters were used in all XCT measurement setups: voltage 200 kV, current 49 µA, 3142 projections, exposure 2000 ms and gain 24 dB. A detector shading correction was applied by averaging 512 reference frames (256 bright and 256 dark) and a warmup scan of approximately one hour was performed prior to scans. A 0.5 mm copper pre-filter was used between the X-ray source and the specimen. All measurements were set up in such a way that image resolution was limited by detector pixel size as opposed to the focal spot, in order to neglect the influence of the focal spot size on measurement data. X-ray imaging and volumetric reconstruction were performed using manufacturer's proprietary software (X-Inspect and CT-Pro, respectively), using the FDK algorithm [27] with a second order beam hardening correction and a Hanning noise filter, with cut-off at the maximum spatial frequency. This filter was chosen to reduce image noise present when alternatively using an