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Marc-Antoine de Pastre[1], Yann Quinsat[1], Claire Lartigue[1]

[1]LURPA, ENS Paris-Saclay, Université Paris-Saclay, 91190 Gif-sur-Yvette, France

marc-antoine.de_pastre@ens-paris-saclay.fr

Abstract

As one of the main additive manufacturing (AM) advantages, lattice structures are being studied in many applications such as vibration attenuation, weight reduction of components or optimised heat exchangers. However, lattice structures are challenging to produce, and may present some shape defects. Although significant works have been performed in lattice structure defect observations such as overhanging features or resulting porosity, there has been relatively less research in modelling shape defects by defining a geometric description approach. In this paper, a Virtual Volume Correlation (V2C) method is proposed in order to identify metal laser powder bed fusion (LPBF) BCCz struts shape defect directly from volumetric data obtained by X-ray computed tomography (XCT). In the proposed V2C method, a correlation score is calculated between the volumetric data and a virtual volume. This virtual volume is determined according to the computer-aided-design (CAD) model and a shape defect which is defined using a linear decomposition relying on a user-defined defect basis. Shape defects of the studied part are successively, according to a Newton Raphson optimisation scheme, determined by correlation score minimisation. Vertical and inclined beams have been printed and measured with XCT and focus variation (FV). Strut geometries obtained with V2C methodology are compared with extracted $ISO_{50\%}$ point clouds, on the one hand, and measured FV point clouds, on the other hand, by computing signed cloud-to-mesh distances. These comparisons bring out that the V2C method is efficient to identify strut shape defects directly from volumetric data, without any post-reconstruction XCT data treatment. The simplification of these data treatment steps then raises the direct and accurate CAD feedback opportunity. Conclusions are drawn regarding the suitability of the proposed V2C method and its further development to more complex LPBF structures.

Computed tomography, virtual volume correlation, modal decomposition, shape defect identification

1. Introduction

With the design freedom enabled by additive manufacturing (AM), complex geometries are not limited by subtractive or formative manufacturing constraints anymore [1]. Lattice structures, which are increasingly studied in the AM field, consist of an elementary cell regularly repeated in the 3D directions to form a network [2, 3, 4]. Lattice structures are not free from defects, which have been reviewed by Echeta *et al.* [4] for powder bed fusion (PBF). Measurement of these defects are mainly performed using computed tomography (CT) for its ability to assess either internal or external dimensional deviations [4, 5]. However, CT dimensional measurements rely on the material boundary determination introducing a threshold uncertainty, prior to any further data treatments [6, 7, 8]. There have been significant efforts in reducing this uncertainty with sub-voxel studies [8, 9] or more recently by conformance approach [10].

In this paper, a virtual volume correlation (V2C) method is proposed in order to find form defect of body-centered cubic with vertical struts geometry (BCCz cells), directly from volumetric data, without boundary thresholding nor additional data treatment. Indeed, recent works have highlighted the interest of virtual correlation techniques for contour or envelope identification in different fields. In the medical field, virtual correlation methods are applied for modelling pelvic organs from magnetic resonance imaging (MRI) volumetric data [11]. In the mechanical field, virtual correlation techniques have proven their interest for shape boundary identification of curved and elongated structures [12, 13].

The aim of this paper is to assess the proposed V2C method applied to lattice beams relying on a defect basis description. V2C estimated form defect will be compared to extracted $ISO_{50\%}$ and measured focus variation (FV) [14] point clouds. In section 2, the V2C method is presented and assessed using vertical and inclined struts, which is representative of a BCCz lattice structure. Results are presented in section 3 and discussed in section 4.

2. Methodology

2.1. Virtual volume correlation

Let f be a physical volume, containing a closed envelope whose displacement field $\mathbf{u}$ should be identified in comparison to an original regular shape. Let $\{\boldsymbol{X}_f\}$ be the voxels defining that envelope. Similarly, let g be a virtual volume and $\{\boldsymbol{X}_g\}$ the voxels defining the virtual envelope. Each point of the physical envelope can be written as:

$$\boldsymbol{X}_f = \boldsymbol{X}_g + \boldsymbol{u} \qquad (1)$$

V2C consists in iteratively minimising the grey level differences between physical and virtual volumes using the least square criterion. A correlation score Φ should be introduced as:

$$\Phi(\boldsymbol{u}) = \iiint_{ROI} [f(\boldsymbol{X}) - g(\boldsymbol{X} + \boldsymbol{u})]^2 d\Omega \qquad (2)$$

where ROI refers to the region of interest in terms of considered voxels, and $\{\boldsymbol{X}\}$ refers to considered voxels in the physical volume f. The displacement field $\boldsymbol{u}$ only applies to the virtual contour points, and can be described as a sum of modes i.e. elementary displacement fields. Whereas previous works often modelled strut shape defects as first order ellipse approximations [15, 16], modal decomposition methods [17, 18, 19] consist in expressing the form defect as a linear combination of elementary displacements:

$$\boldsymbol{u} = \sum_k \lambda_k \boldsymbol{u}_k \qquad (3)$$

where λ_k are the components of $\{\boldsymbol{\lambda}\}$ and refer to the modal amplitude i.e. the amplitude of the elementary displacement descriptor $\boldsymbol{u}_k$ and are defined by:

$$\{\boldsymbol{\lambda}^*\} = \underset{\boldsymbol{\lambda}}{argmin}\, \Phi(\boldsymbol{u}) \qquad (4)$$

λ_k^* are found by combining equations 2 and 3 using a Newton-Raphson optimisation. An illustration of V2C application is shown in Figure 1 for a 2D example of a strut cross-section. From volumetric data (Figure 1a), the shape defect is initially taken as a nominal circle (Figure 1b), and is iteratively identified (Figure 1c).

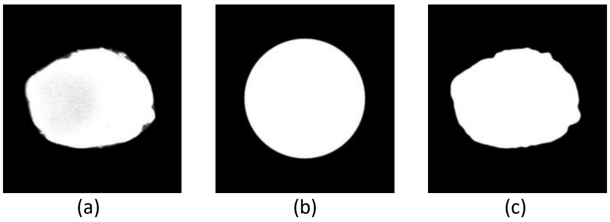

Figure 1. Illustration of V2C on a 2D strut cross-section: (a) XCT physical measurement; (b) initial virtual shape; (c) computed virtual shape defect

2.2. Shape defect basis

This section particularly focuses on the elementary displacement descriptors $\boldsymbol{u}_k$ introduced in equation 3. In previous virtual correlation works, Semin *et al.* [13] used segmentation 2D descriptors to identify elongated curvilinear shapes whereas Jiang *et al.* [20] and Rhétoré *et al.* [21] used Bspline curves. Jiang *et al.* [11] extended the methodology to the 3D modelling of pelvic organs relying on NURBS geometric descriptors.

In this work, as lattice beams are studied, displacement descriptors $\boldsymbol{u}_k$ are introduced considering cylinder defects. Indeed, for this geometry, Homri *et al.* [22] noted the modal decomposition usefulness for cylinder shape defect identification.

Therefore, the displacement field is assumed to be four-fold:

- Rigid transformations
- Dilatation
- Vertical defects:
  - Vertical section modification descriptors such as taper or barrel modes
  - Vertical rippled modes
- Plane defects defined by sinusoidal descriptors

Figure 2 illustrates some of the considered modes for the chosen shape defect basis.

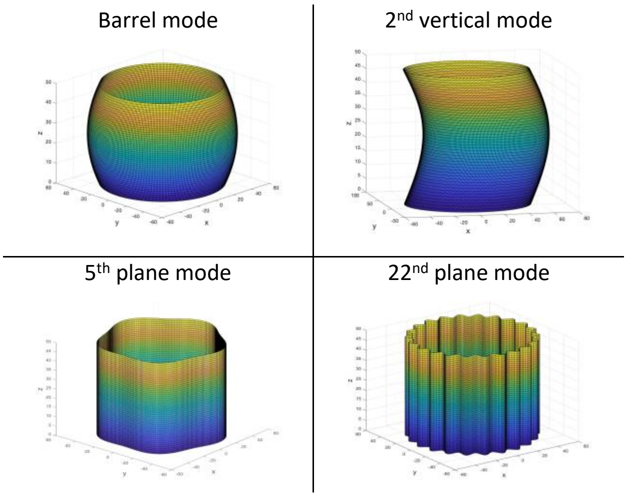

Figure 2. Illustration of some of the considered modes in the chosen basis description (amplitudes have been enhanced for more visibility)

2.3. Sample manufacturing and measurement

2.3.1 Sample manufacturing

Samples consist in vertical and inclined beams in order to be representative of vertical and inclined beams defining a BCCz strut-based lattice structure (see Figure 3). Beam radii have been set to 0.6 mm and have a 5 mm length. Samples were produced by laser PBF on an Addup FormUp 350 using Inconel 718 powder and the printing parameters displayed in Table 1.


Figure 3. Vertical and inclined BCCZ representative printed struts. (One strut from each set has been considered in the following)

Table 1: Printing parameters

Powder	Inconel 718
Layer thickness	40 µm
Laser power	220 W
Scan speed	2100 mm.s^{-1}
Contour scan power	210 W
Contour scan speed	1800 mm.s^{-1}
Hatch space	55 µm

2.3.2 Sample measurements

Each beam was measured using X-ray CT and FV instruments. Measurement setups are provided hereafter:

- XCT: geometric magnification of 33 % leading to a voxel size of 9 µm. Volumetric reconstruction was performed from 900 projections, tube voltage 150 kV, tube current 40 µA. Projections were saved in a .raw file format.
- FV: 10× objective lens with long working distance, numerical aperture 0.3, field of view (2.05 × 2.05) mm, pixel lateral resolution 2.07 µm, optical lateral resolution 0.91 µm, contrast lateral resolution 0.53 µm, coaxial

illumination, stage rotation step of 50°, fusion of multiple field of views performed in the manufacturer's software, measured volume after data fusion (1.3 × 1.3 x 5.6) mm

2.4 V2C assessment pipeline

Using the chosen shape defect basis, volumetric data from XCT are directly used by V2C to compute the correlated virtual envelopes for each strut, saved as a point cloud which is thus meshed. For each strut, the correlated mesh is compared to respectively extracted $ISO_{50\%}$ and measured FV point clouds, by computing cloud-to-mesh distances. Figure 4 summarizes the different steps of the process.

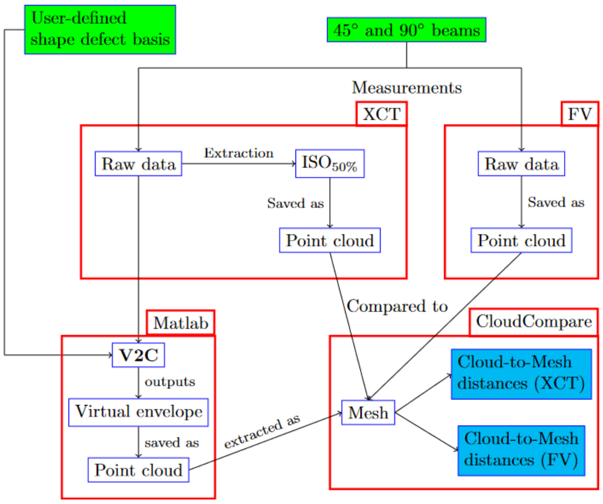

Figure 4. Data processing pipeline. Inputs are filled in green and outputs are filled in blue.

3. Results

Figure 5 displays, for both 45° and 90° struts, cloud-to-mesh distances between correlated envelopes and point clouds stemming from $ISO_{50\%}$ and FV sets. Results show that mean discrepancies between correlated mesh and point clouds are relatively the same for both $ISO_{50\%}$ and FV comparative sets, in both strut cases. In addition, standard deviation estimations are consistent whatever the comparative set, with values around 26 µm.

4. Discussion

For the 45° strut, standard deviations show more discrepancies between $ISO_{50\%}$ and FV sets when compared to the correlated mesh obtained using V2C. This observation may be explained by the surface topography of the 45° strut in comparison to the 90° strut. As a matter of fact, during the manufacturing process, 45° struts down-facing surfaces have no supporting structures, resulting in a poor strut surface quality. When measured using XCT, these rough surfaces alter V2C identification.

Moreover, these surfaces have an increased FV measurement uncertainty, impacting the resulting standard deviation when compared to correlated mesh. Indeed, as shown in Figure 5 for the 45° strut, standard deviations are 4 µm higher in the correlated-FV set than in the correlated- $ISO_{50\%}$ set. Conversely, the 90° strut is not impacted by the absence of supporting structures, resulting in a regular surface topography all around the strut. That is why, in Figure 5, for the 90° strut, standard deviations are about the same value.

For both 45° and 90° struts, estimated standard deviations are about the same value which is between 2.5 and 3 times the XCT resolution.

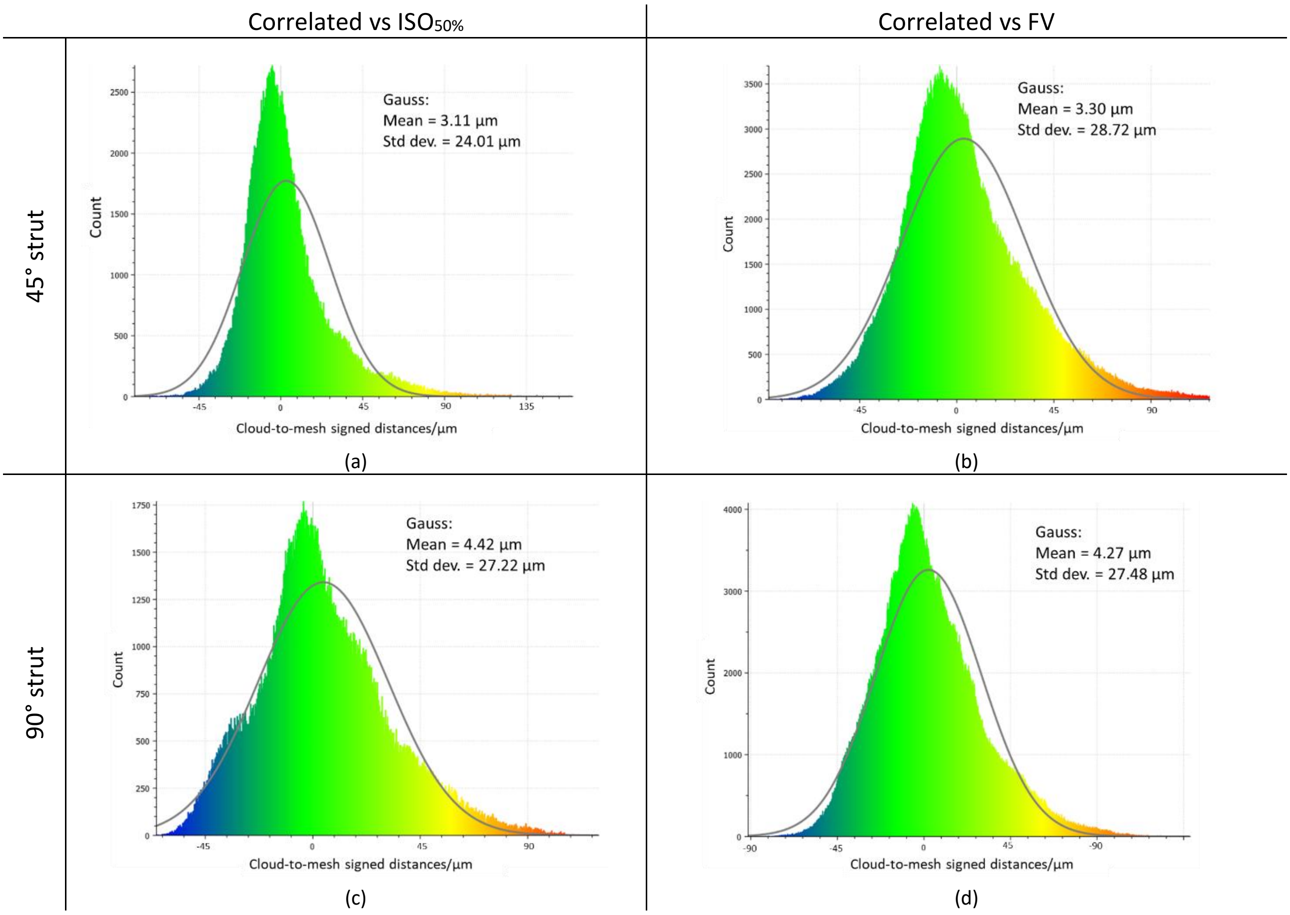

Figure 5. Computed cloud-to-mesh distances for both struts: (a) and (c) correlated vs $ISO_{50\%}$ point clouds; (b) and (d) correlated vs FV point cloud

These values are relatively low regarding the objective of studying shape defect. Thus, V2C provides a good estimation of lattice strut shape defect, performing the strut roughness separation from shape defect.

5. Conclusion

This paper showed the suitability of the proposed V2C method to identify strut shape defect directly from volumetric measurements, without any additional XCT data treatment. Moreover, the noteworthiness of V2C is to extend shape defect determination relying on modal decomposition relatively to a user-defined defect basis.

However, modal decomposition raises the number of considered modes question. Future works will focus on more precise sensitivity studies in order to better understand how the number of considered modes, as well as the chosen defect basis, will impact the correlated shape defect.

Future works will also focus on a meshed version on V2C adapted to entire lattice structures in order to broaden CAD feedback opportunities.

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