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X-ray computed tomography dimensional measurements of powder bed fusion cellular structures

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Abstract
Metal parts with controlled cellular structures can be produced via additive manufacturing technologies. However, critical aspects of additively manufactured products include poor geometrical accuracy and complex surface morphology, which can lead to mechanical properties degradation and product failure. To control and improve these aspects, X-ray computed tomography can be applied, enabling advanced three-dimensional non-destructive evaluations of both external and non-accessible features. In this work, Ti6Al4V cellular structures with different periodic lattice designs produced by powder bed fusion were analysed using a metrological X-ray computed tomography system. In particular, challenges and accuracy of CAD comparison and thickness analyses were studied through specific experimental and simulation investigations, taking into account also the influence of structural distortions and surface morphology.

X-ray computed tomography, cellular structures, powder bed fusion, dimensional metrology.

1. Introduction

Additive manufacturing (AM) technologies are increasingly expanding in several industrial sectors, including the production of components with complex geometry and high structural complexity [1]. In particular, the powder bed fusion technology can be used to fabricate strong and complex metallic lattice structures [2], which are impossible to be obtained through conventional manufacturing techniques (e.g. machining and casting). The production of such lattice structures is relevant in biomedical engineering for the replacement and stabilization of damaged bone tissue [3]. However, AM products are inherently characterized by poor geometrical accuracy and complex surface morphology, which can lead to mechanical properties degradation, product failure and significant differences between designed and as-produced parts [4]. In order to verify the quality of AM lattice structures and to optimize the AM process, accurate dimensional measurements are needed. Metrological X-ray computed tomography (CT) is an advanced three-dimensional measuring technique that can be effectively used for AM components, including cellular specimens [5], as it is capable of examining non-destructively features and structures that are inaccessible with other measuring techniques [6]. Examples of CT evaluations that can be performed on cellular components are CAD comparison and thickness analysis [7]. Investigations performed in this work were focused on studying challenges and accuracy of such dimensional analyses on cellular structures produced via powder bed fusion.

2. Materials and instrumentation

In this work, cellular specimens with different periodic structures produced by powder bed fusion of Ti-6Al-4V alloy [3] were investigated. The specimens were scanned using a metrological CT system (Nikon Metrology MCT225) characterized by micro-focus X-ray tube, 16 bit detector with 2000×2000 pixels, high-accuracy linear guideways and thermally controlled cabinet. The chosen scanning parameters are: voltage 180 kV, current 38 µA, exposure time 2000 ms and voxel size equal to 8.3 µm.

3. Description of CT-based analyses

3.1. CAD comparison

The CT-measured geometries were compared with the same CAD model utilized for the production of the samples using the analysis and visualization software VGStudio MAX 3.1 (Volume Graphics GmbH, Germany) after aligning the actual volume with the nominal model by means of Gaussian best-fit. The outcome of the comparison is a color-coded map of deviations, as shown in Figure 1 (a).

3.2. Structural distortions

A new routine was implemented in Matlab (MathWorks, USA) to identify the spatial coordinates of nodes using a point cloud extracted from the CT scanned volumes. The actual position of nodes was then compared with their nominal position (see Figure 1 (b)).

3.3. Thickness analysis

The thickness distribution of the cellular structures was evaluated using a dedicated module of VGStudio MAX 3.1 and was then compared with the nominal thickness. Such analysis does not require an alignment between measured geometry and nominal model. The main parameter to be defined is the search angle, centred on the lines perpendicular to the two opposite surfaces considered for the starting point and the end point.

3.4. Evaluation of surface topography

CT has been recently utilized for topography evaluations of AM surfaces [8], including surfaces not accessible by other instruments. The evaluation of surface roughness is relevant also because it can influence the dimensional measurements performed by CT [9]. In this work, the surface of cellular specimens was analysed on areas randomly selected inside the part on nominally cylindrical portions after the subtraction of a least-squares mean cylinder (surface S-F), in terms of *Sa* and *Sz* parameters in accordance with ISO 25178-2:2012-Part 2 [910

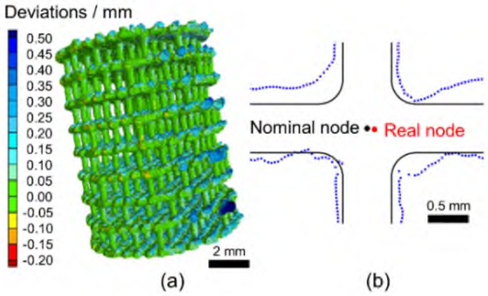

Figure 1. (a) Color-coded map of deviations between CT-measured part and nominal model. (b) Real node (red point, obtained by CT data) compared with the corresponding nominal node (black point). Black solid lines represent the CAD model and blue dotted lines represent the measured surfaces.

4. Results and discussions

The comparison between each CT-measured part and the corresponding nominal model (see Section 3.1) showed deviations which are mainly positive for each specimen while the structural distortions analysis (see Section 3.2) revealed that significant structural distortions characterize the as-produced specimens. The deviations determined from the CAD comparison include both geometrical/dimensional errors and structural errors. For this reason, when the interest is on evaluating only the errors associated with the local dimensions, a thickness analysis is more effective. A first thickness analysis (see section 3.3) was conducted using the default value proposed by the software for the search angle (i.e. 30°). An anomalous peak of very low thickness was found for each specimen, as visible in Fig. 2 (a) where two specimens (A and B) are taken as examples. The relevance of these peaks was observed to be strongly related to the search angle (see section 3.3) and to the complex topography of the surface. In fact, sample A has a higher roughness than sample B (see Figure 2 (a)): *Sa* and *Sz* parameters are 27 and 267 µm respectively for sample A, and 19 and 157 µm for sample B. The peaks were observed to decrease systematically by changing the search angle (e.g. systematic decrease of 70 % by changing the search angle from 30° to 15°) as shown in Fig. 2 (a) for sample A.

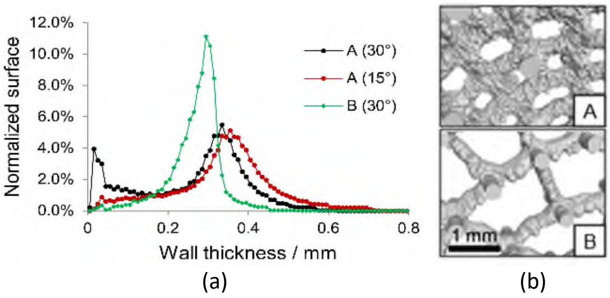

Figure 2. (a) Thickness distribution for samples A (search angle 15° and 30°) and B (search angle 30°). (b) Regions of interest of samples A and B; different surface topographies can be observed for the two samples.

The combined influence of surface topography and search angle on the thickness analysis was analysed by simulating the CT scan of five cylindrical features with height equal to 1 mm and topography representing different combinations of roughness and waviness, obtained from the 360°-rotation of the following functions around the central axis: C1: $y = 0.17$; C2: $y = 0.17 + (\sin 10x/100)$; C3: $y = 0.17 + (\sin 40x/100)$; C4: $y = 0.17 + (\sin 10x/100) + (\sin 80x/200)$; C5: $y = 0.17 + (\sin 10x/100) + (\sin 160x/200)$. Figure 3 reports the percentage deviations obtained by comparing the measured mean thickness (weighted on the surface area interested by each thickness) with its corresponding reference value. The error related to the mapped surface (i.e. the surface actually analysed by the algorithm) is reported as well. The search angle 15° was determined to allow mapping well the surface while keeping deviations under 5%. The same cylindrical features were used to investigate the influence of different surface topographies on the CAD comparison analysis. Results obtained using C1 as reference show percentage deviations below 2.3% in absolute value.

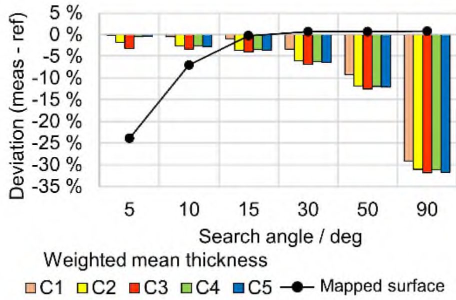

Figure 3. Relative deviations (measured - reference) of the five simulated cylindrical features (C1, C2, C3, C4, C5), concerning the mean thickness (weighted on the surface interested by each thickness) and the mapped surface, for different search angles.

5. Conclusions

In this work, Ti-6Al-4V cellular specimens produced by powder bed fusion were analysed in terms of CAD comparison and thickness distribution. It was investigated how CAD comparison analyses can be influenced by structural distortions which can often occur in cellular structures produced by additive manufacturing. Moreover, thickness analysis was found to be sensitive to the surface topography and the search angle. The search angle was optimized by evaluations performed on five simulated cylindrical features, enabling an improvement in accuracy of the thickness analysis of SLM specimens.

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