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Evaluation of defects in laser powder bed fusion metal parts via in-process optical measurements and post-process X-ray computed tomography

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Abstract
Laser powder bed fusion (LPBF) enables the fabrication of metal parts characterized by high geometrical complexity, unique possibilities of customization and increasingly good mechanical properties. However, parts produced by LPBF are often characterized by poor geometrical and dimensional accuracy as well as by a number of internal defects, which undermine a wider application of LPBF in industry. Several in-process measurement methods have been proposed to identify out-of-control process conditions and take immediate action, as well as to improve the understanding of the LPBF process. However, the correlation between in-process measurement results and actual defects in the fabricated parts is not always clear yet. This work presents an experimental study aimed at defining a reproducible methodology for comparing optical in-process evaluations to X-ray computed tomography post-process measurements of actual defects.

Additive manufacturing, X-ray computed tomography, optical metrology, in-process measurements

1. Introduction

Among metal additive manufacturing (AM) technologies, laser powder bed fusion (LPBF) is gaining particular interest from high-value industrial sectors, such as automotive, aerospace and biomedical [1]. Compared with conventional manufacturing processes, LPBF can fabricate metal parts with higher geometrical complexity, unique possibilities of customization and good strength-to-mass ratio. However, LPBF is still often characterized by manufacturing issues that can lead to poor geometrical and dimensional accuracy, high defect rate, and consequent product failure and/or parts rejection [2].

The layer-wise manufacturing of LPBF can be exploited to acquire process-related inner measurements directly when the part is being fabricated. The acquired information can be used, for example, to identify out-of-control conditions/events and take actions with feedback control systems [3]. In addition, the gathered information is useful to increase the knowledge on LPBF and improve the process itself. Even if several in-process methods have been proposed in literature to measure different types of process signatures (e.g. melt pool, powder bed quality and layer geometry [4]), the correlation between in-process measurement results and the characteristics of actual defects in the fabricated parts is not always well-understood yet.

This experimental work investigates a reproducible methodology for comparing in-process optical measurements to post-process X-ray computed tomography (CT) measurements. Metrological CT was chosen for the post-process analyses as it is capable of obtaining, in a non-destructive way, three-dimensional (3D) reconstructions of fabricated AM parts that can be used to measure external as well as internal geometries, features and micro-features [5].

2. Materials and methods

Design and production of specimens are briefly presented in Section 2.1, the setup used for in-process optical measurements is addressed in Section 2.2 and post-process tomographic measurements are described in Section 2.3.

2.1. Design and production of specimens

The specimens produced and analysed in this work were designed to enable an accurate alignment and comparison between layer-wise in-process optical measurements (see Section 2.2) and post-process measurements conducted on corresponding slices extracted from CT reconstructions (see Section 2.3). The designed geometry can be seen in Figure 1a: it is composed of four different layer geometries (represented in red colour in Figure 1b) extruded and stacked vertically (along the build direction).

Specimens were produced via LPBF of Ti4Al6V, using a Sisma MYSINT100 (Sisma, Italy). Figure 1a illustrates the designed support structure and how the specimens were positioned onto the build platform.

2.2. In-process optical measurements

Layer-wise in-process optical measurements were performed using the setup schematized in Figure 2a. A consumer-grade 18 mega pixel digital single-lens reflex (DSLR) camera, with an off-axis positioning with respect to the laser direction, was used to acquire images of the entire build platform with a field of view (FOV) equal to 5184×3456 pixels, in two moments: (i) right after recoating and (ii) after laser exposure. This work will focus on the layer images acquired after laser exposure. A side light was used as source of illumination. The obtained images were corrected in terms of perspective and scale using a reference hole plate with calibrated dimensions, which was imaged on the build platform using the same optical setup before starting the LPBF process. The corrected images (with pixel size equal to 15 µm) were then elaborated in Matlab (Mathworks, USA) to determine for each fabricated layer: (i) the geometry contour using a local-adaptive algorithm and (ii) the potential internal defective regions using a global thresholding. Figure 2b shows an example of corrected image and Figure 2c the determined contour profile.

2.3. Post-process CT measurements

A metrological micro-CT system (MCT225, Nikon Metrology, UK) was used to scan the LPBF specimens, setting the X-ray tube voltage at 180 kV, the current at 38 μA and the exposure time at 2000 ms. A 0.1 mm copper physical filter was interposed between the X-ray source and the scanned sample to reduce beam hardening. The achieved voxel size was equal to 4.5 μm. The obtained CT reconstructions were imported in the visualization and acquisition software VGStudio MAX 3.2 (Volume Graphics GmbH, Germany) to (i) determine the surface with local-adaptive algorithms, (ii) compare the as-built geometry with the nominal design and (iii) evaluate the internal porosity in terms of size, shape and spatial positioning.

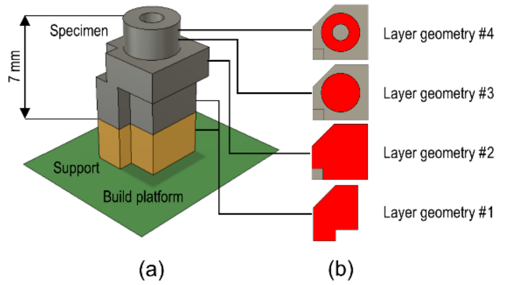

Figure 1. Schematic representation of the specimens' geometry (shown in grey), support structure (in yellow) and chosen position onto the build platform (in green) (a); four layer geometries (cross-sections shown in red) composing the specimens' geometry (b).

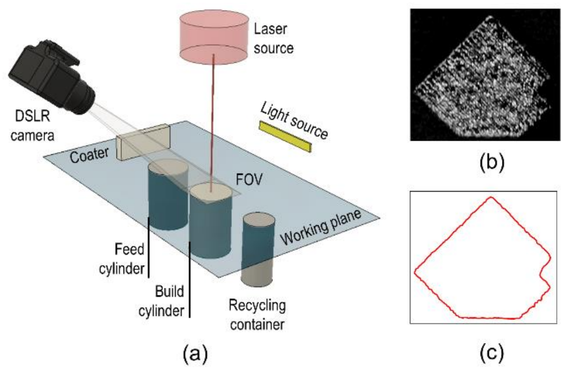

Figure 2. Setup of in-process optical measurements (a); example of image acquired with the DSLR camera after perspective and scale correction (b); determined edge boundary (c).

3. Results and discussion

The contour profiles determined for each layer as explained in Section 2.2 were stacked with vertical spacing equal to the layer thickness, to obtain a 3D reconstruction of the lateral sample geometry. Both optical and CT reconstructions were compared with the computer-aided design (CAD) model. Figures 3a-b and 3d-e show the deviation maps resulting from such comparisons, in which deviations are expressed in millimetres and associated to a colour scale. For some geometrical features, the deviations determined with optical measurements clearly differ from those found with CT (see for example differences at corners and edges identifiable in Figure 3); however, the optical measurements are capable of gathering information on the major actual geometrical deviations. It is worth noting that some differences between in-process and post-process measurements are clearly related to specific process-dependent effects, e.g. residual stresses – inducing post-fabrication deformations – and other consequences of the sintering mechanism – leading to the formation of non-completely melted powder particles onto the samples' surfaces after the fabrication of the specific layer. In addition, it can be observed that in the unsupported overhang region the surface folds up, generating an out-of-plane deformation and negative deviations in the CT reconstruction (see Figures 3d-e). However, in the same region reconstructed from optical measurements, deviations have wrong sign with respect to deviations found with CT (see Figures 3a-b); this is due to the perspective correction of optical images which does not take into account possible out-of-plane deformations, hence determining the errors of out-of-plane regions.

Figures 3c and 3d compare the internal defects detected on a cross-section during the process and after the fabrication, respectively. In-process optical measurements were capable of detecting the three largest actual pores. However, false positives were found especially close to the upper borders, i.e. those characterized by the folded-up surface that generate a dark shadow on the acquired layer image.

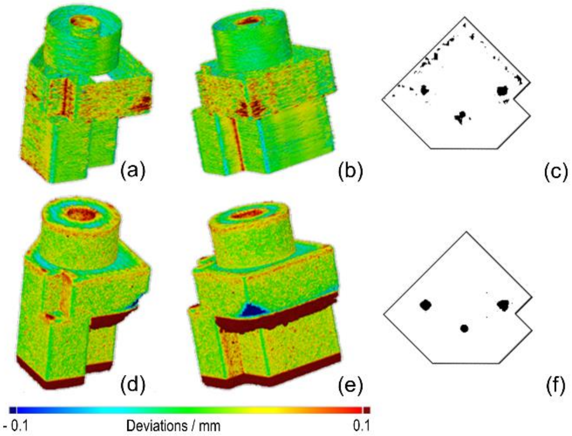

Figure 3. CAD comparison related to in-process optical reconstruction (a,b) and post-process CT reconstruction (d,e). Dark red regions in CT reconstruction are related to dross formation, which cannot be measured in-process. Potential internal defects measured with the optical setup (c) and actual defects measured by CT (f).

4. Conclusions

This paper presented a preliminary work focused on the comparison between optical in-process evaluations of defects of LPBF metal parts and X-ray computed tomography post-process measurements of actual defects. Results have shown that the used optical setup is capable of gathering dimensional data which can be used to evaluate internal defects and geometrical deviations with respect to the as-designed geometry. Differences with respect to post-process CT measurements were observed and their causes identified. Future works will be focused on improving the proposed in-process measurement setup and the comparison of in-process and post-process defect evaluations, starting from the critical aspects outlined in this study.

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