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On the alignment of in-process and post-process measurement datasets acquired for precision enhancement of laser powder bed fusion of metals

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Abstract
Despite laser powder bed fusion technology is spreading widely among several industrial sectors, the process can be affected by low repeatability and manufacturing issues leading to defects formation. Therefore, the development of in-process monitoring systems aimed at detecting possible defects during the fabrication is of increasing interest. In this context, process events must be correlated to actual defects, which implies the need for an accurate comparison between datasets acquired by in-process and post-process measurements. This work is focused on the development of a sample geometry specifically designed for the accurate registration of datasets, which was demonstrated to be fundamental to improve data correlation, but is complicated for example by part distortions occurring after fabrication. The proposed method was verified through a case study, in which it was successfully implemented to correlate in-process hot spot detections with the induced pores measured by post-process X-ray computed tomography.

Additive manufacturing, Metrology, X-ray computed tomography, Process monitoring, Data registration

1. Introduction

The interest towards laser powder bed fusion (LPBF) has rapidly increased over recent years for its capability of fabricating metal components with high geometrical complexity and good mechanical properties [1]. A wider adoption of LPBF in relevant industrial sectors is however hindered because the manufactured parts still often present poor dimensional accuracy and a high defect rate, demanding for intensive post-process quality control as well as time-consuming and expensive after-build operations. This motivates the current research efforts devoted to the development of real-time monitoring solutions, for detecting process defects at their early onset stage. In spite of several sensors have already been tested to acquire data linked to different process signatures [2], the correlation between in-process detected anomalies and post-process measured defects has still to be clearly demonstrated [3]. In particular, an important issue is related to the alignment between in-process and post-process data, which is complicated by the deformations and dimensional deviations occurring due to the heating/cooling cycles, during and/or after the fabrication [1]. Moreover, the majority of previous studies investigating the correlation have been conducted using specimens with simple geometries, e.g. cylinders and cubes, without fiducials to aid the alignment operations [4]. An interesting work dealing with data registration can be found in [5], where relevant design guidelines were pointed out. Work is still needed to optimize the sample geometry.

This work is focused on the design of a geometry specifically intended for the enhancement of the alignment of in-process acquisitions with post-process X-ray computed tomography (CT) measurements. Design for additive manufacturing and design for metrology principles were adopted. A case study is addressed, showing that the correlation between outlier process events and actual defects can be determined more accurately using the designed geometry.

2. Sample design and alignment methodology

The sample geometry was designed taking into account the following manufacturing- and metrology-related requirements: (i) the sample envelope dimensions should enable high resolution CT scans, while maintaining at the same time a volume suited for representative defects analyses, (ii) the alignment fiducials should be measurable with minimized influence of form errors and surface texture, (iii) the fiducials should be well integrated in the global sample geometry to be affected by the overall deformations and not by other localized deformations, and (iv) a number of subsequent reference planes should be measurable along the building direction to detect possible in-plane as well as out-of-plane geometrical deviations that need to be considered in the alignment steps.

The proposed geometry is illustrated in Figure 1. The initial shape is a cylinder placed on a flat base (plane A, highlighted in red colour in Figure 1). The base plane normal was used as reference to identify the building direction (z-axis). 21 internal pockets were then generated to host cylindrical features (an example is C in Figure 1). The pockets are placed at seven different levels along the cylinder axis, three for each level, at a relative angle of 120°.

Each cylindrical feature and the corresponding bottom planes (an example is P in Figure 1) are then used for least-squares fitting. The intersections of the cylinders' axes with the bottom planes are used to determine three points for each considered level. Such points are used to generate seven reference planes. The CT cross-sections extracted using these planes can be compared to the corresponding layer-wise analyses performed during the process. An earlier version of this geometry employed spheres instead of cylinders as alignment fiducials, but experiments showed that the dross formation and the staircase effect did not enable a reliable fitting of the spheres. Vertical cylindrical features were hence chosen to avoid both dross formation and staircase. In addition, they were not modelled as separated entities, but they were instead partially integrated to the main cylinder to guarantee a good heat dissipation during the process and prevent possible isolated local deformations. The size of the cylindrical fiducials was designed to be large compared with the order of magnitude of surface imperfections and texture, thus ensuring a good fitting in post-process inspection. In order to reduce the effect of surface texture on the fitting of reference planes (i.e. A and P planes), they were subjected to laser remelting before starting the production of the successive layer.

Finally, a notch was also included in the base to ease the first rough alignment.

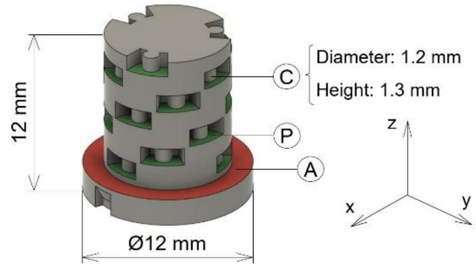

Figure 1. Schematic representation of the sample design.

3. Verification of the alignment method

Specimens with the design described in Section 2 were produced via LPBF of Ti6Al4V using a Sisma MYSINT100 (Sisma SpA, Italy). Process parameters and support structures were purposely set to induce the formation of lack-of-fusion defects and to stimulate geometrical deviations and warping.

After the manufacturing process, a metrological micro-CT system (MCT225, Nikon Metrology, UK) was used to scan the specimens with a voxel size equal to 7.7 µm, which is sufficient for porosity analysis [6]. The reconstructed 3D volumes were then elaborated through the software VGStudio MAX 3.2 (Volume Graphics GmbH, Germany), where the fitting of the geometrical elements was carried out as described in Section 2.

A first global registration between the CT reconstruction and the nominal model was done considering only the base plane, the notch and the larger cylindrical geometry. Figure 2b shows as an example the CT cross-section corresponding to the 4th level, obtained by virtually sectioning the CT volume using the nominal plane at that level. It can be observed that the obtained cross-section geometry does not correspond to the nominal one (Figure 2a), due to the deformation of the fabricated part. As expected, the global registration was hence proven not adequate to accurately align CT cross-sections with corresponding in-process acquisition, in case of part deformations occurring after the production of the specific layer. When computing the alignment using the fiducials and the method described in Section 2, the resulting cross-section is shown in Figure 2c.

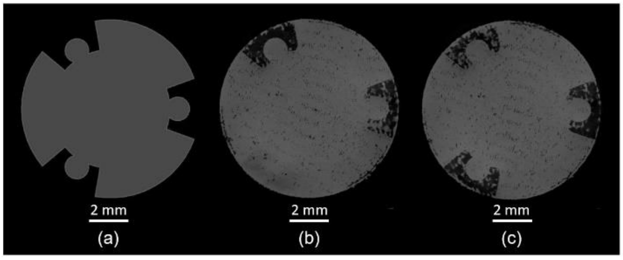

Figure 2. Comparison of a nominal cross-section (a) with actual CT cross-sections extracted using a global alignment (b) and the alignment method proposed in this work (c).

4. Comparison of in-process and post-process data

The proposed alignment methodology was implemented for the comparison of data acquired during the LPBF process using an optical off-axis system with X-ray CT post-process measurements. In particular, a DSLR camera was employed to acquire a long-exposure image of each fabricated layer from a lateral view direction with respect to the laser direction. Figure 3a shows an example of an obtained image, while Figure 3b shows the corresponding CT cross-section obtained after applying the alignment method proposed in this work. As represented, a hot spot caused by a spatter particle was detected during the process, exactly where the corresponding CT section showed a lack-of-fusion defect surrounding a solid round feature.

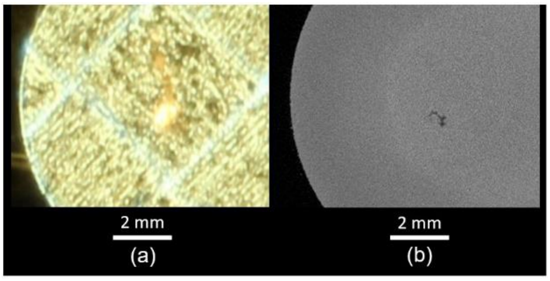

Figure 3. Comparison of a long-exposure image gathered during the process (a) with the corresponding post-process CT cross-section (b).

5. Conclusions and future work

This work was focused on the accurate alignment for a robust comparison of in-process and post-process data, which is fundamental to enhance the understanding and the precision of LPBF of metals. The proposed geometry and alignment method were experimentally verified by producing LPBF metal parts with purposely induced defects and deformations. Improved results were obtained compared to the global alignment, which cannot take into account deformations occurring after the generation of the specific layer. The methodology was also applied to a case study where hot spots due to spatter particles detected during an actual LPBF process could be correctly correlated to the corresponding induced pores revealed by the post-process CT analysis. Future works will be focused on further verifying the alignment methodology. The proposed geometry can be improved, for example, by increasing the number of vertical reference planes for gathering more dense and detailed information along the building direction.

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