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Towards the improvement of high-speed laser powder bed fusion using aligned datasets obtained from process monitoring based on photodiode signal variation and post-process X-ray computed tomography

Nicolò Bonato[1], Mirko Sinico[2,3], Filippo Zanini[1], Wim Dewulf[2], Simone Carmignato[1]

[1]*Department of Management and Engineering, University of Padova, 36100 Vicenza, Italy*
[2]*Department of Mechanical Engineering, KU Leuven, 3001 Leuven, Belgium*
[3]*Flanders Make@KU Leuven, 3001 Leuven, Belgium*

nicolo.bonato@phd.unipd.it

Abstract
Laser powder bed fusion of metals offers important advantages for several industrial applications. Research work is needed to improve the production rates while reducing the likelihood of defects compromising part quality. It is feasible to improve production rates by fabricating parts with thicker layers, but this often leads to an increased presence of flaws. This work focuses on evaluating the potential of employing real-time monitoring data gathered by means of photodiodes for enhancing high-speed LPBF. Potential sites of defects are compared to actual porosities measured via X-ray computed tomography by applying a methodology that guarantees an accurate alignment and comparison considering part shrinkage and distortions.

X-ray computed tomography, Laser powder bed fusion, datasets alignment, in-process monitoring

1. Introduction

Laser powder bed fusion (LPBF) is increasingly used in a variety of industrial sectors, such as biomedical, aerospace and metal tooling, due to its ability to produce parts with highly complex geometries and good mechanical properties [1]. Despite the suitability of LPBF in various fields, the process still suffers from low production rates [2]. Hence, current research efforts are directed towards improving LPBF productivity by fabricating parts with an increased layer thickness (LT), although components obtained with this strategy are more likely to be affected by internal defects, such as lack-of-fusion porosities, compared to thinner layer thicknesses [3]. Monitoring the process in real time with a particular focus on the detection of lack-of-fusion flaws can provide useful information on part quality and reliability, and – if correctly used – can provide the basis to heal defects while the fabrication takes place. Numerous works are currently addressing this issue; however, determining an effective correlation between monitoring data and actual defects measured with post-process inspection techniques is not a trivial task. In fact, monitored parts are often affected by shrinkage and warpage during and/or after production, which makes it difficult to achieve a reliable comparison between process signatures (i.e. potential sites of defects detected during the process) and post-process data of actual flaws.

This work investigates potential correlations between process defects, measured using metrological X-ray computed tomography (CT), and process signatures discernible from real-time monitoring data in high-speed LPBF. A suitable sample geometry and alignment methodology from [4, 5] were adopted to achieve a reliable correlation between collected datasets.

2. Material and methods

Samples design and fabrication are presented in Section 2.1, together with a description of the used in-process monitoring system. Section 2.2 refers to the post-process analysis with a focus on datasets alignment.

2.1. Sample design, manufacturing and in-process monitoring

Samples were manufactured using a 3D Systems ProX DMP 320B machine (3D Systems Leuven, BE) equipped with a 500 W continuous wave fiber laser with a 90 µm laser spot diameter. Two different approaches were used for enabling a high-speed LPBF fabrication: the first (LT120) with a uniform LT equal to 120 µm throughout the entire layer and the second (LT60-120) with the hull-bulk strategy presented in [6]. In the latter approach, the LT is halved to 60 µm to fabricate the hull of each layer, and maintained at 120 µm for the inner part of the layer, i.e. the bulk region. Parts were produced in M789 tool steel with process parameters reported in [6]. The sample design schematized in Figure 1a enabled accurate alignment and comparison between in-process monitoring data and post-process CT measurements of actual defects, as demonstrated in a previous work [4, 5] and briefly discussed in Section 2.2.

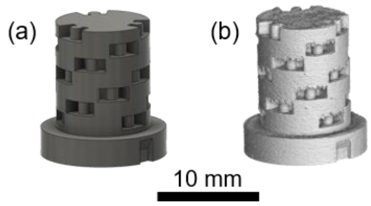

Figure 1. Sample design (a); CT volume reconstruction of a hull-bulk sample (b).

The build job was monitored by means of the machine-integrated *DMP Meltpool* system, based on two photodiodes mounted with a fixed off-axis positioning with respect to the laser source and acquiring a signal proportional to the melt pool emitted radiation intensity at a sampling frequency of 50 kHz [7]. Results reported in this paper will be focused on those obtained with the photodiode placed closer to the samples position on the platform, as it registered signals with higher intensities.

2.2. Post-process analysis and datasets alignment

After the manufacturing process, the samples were scanned using a metrological X-ray micro-CT system (MCT225, Nikon Metrology, UK), reaching a voxel size equal to 8.7 µm. The 3D volumes obtained after reconstruction (see Figure 1b) were then analysed using the software VGStudio Max 2022.3 (Volume Graphics GmbH, DE).

In particular, the alignment methodology outlined in [4, 5] was applied, involving least-squares fitting for cylindrical features and horizontal planes. This approach allows for the derivation of multiple reference points by intersecting the axes of the cylinders with the respective horizontal planes. These reference points are then used to retrieve within CT data the after-build position of the monitored layers, which might significantly change due to shrinkage and local distortions occurring during and after the LPBF process itself. By means of this improved alignment, CT cross-sections can be more accurately compared to the actual corresponding layer-wise monitoring data.

3. Comparison between monitoring and CT data

CT scans of samples fabricated with the two strategies explained in Section 2.1 shown that both approaches led to the presence of some internal porosities. With reference to the LT60-120 sample, few flaws seem to originate in the overlapping zone between the hull and bulk building strategy. In Figure 2a an example of such a pore detected by CT is reported. The gathered photodiode signals (see Figure 2b) - which can be accurately compared with post-process CT data thanks to the improved alignment described in [4, 5] - exhibit peaks of intensity at the corresponding layer, with this behaviour persisting for a few layers above, typically ranging from two to three layers in the observed cases. Subsequently, the signal distribution reverts to more uniform values starting from the fourth layer above the region where the defect was firstly observed in the CT volume.

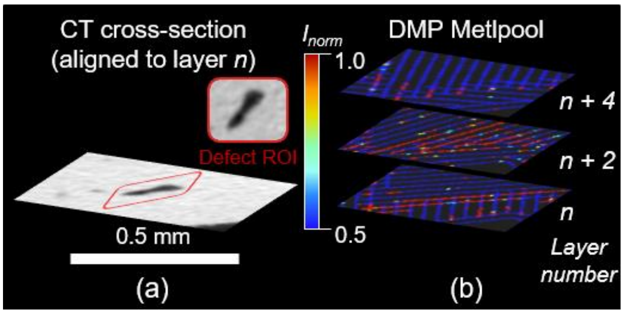

Figure 2. Example of CT cross-section with the presence of an internal pore (a), and corresponding in-process data showing normalized photodiode signal intensity *(I_{norm})* across the layer of interest and following ones (b).

This pattern can also be observed in the graph of Figure 3, where descriptive statistics metrics were monitored throughout the layers for a region of interest containing the defect. As can be seen, the increased number of peaks is confirmed by a wider interquartile range and by a higher likelihood of values above $I_{norm,75}$, as confirmed by the whiskers extended up to $I_{norm,95}$.

Besides the above-mentioned pores, CT scans of samples produced with the LT60-120 hull-bulk approach revealed also the presence of a few porosities of a different type, which seem to originate around solid spherical particles with a size larger than the size of the original powder. These pores are most probably caused by spatters generated due to the particular hull-bulk strategy [6], since CT scans of samples fabricated with the LT120 strategy did not show this specific kind of defects, presenting only a low porosity content as already reported in [6]. Defects of the first type (Figure 2) and with an equivalent diameter equal or greater to 150 µm resulted detectable during the process from increased signal peaks sensed with the off-axis photodiode monitoring system. However, voids of the second type ranging around 150-220 µm of equivalent diameter and caused by the undesired presence of spatter particles did not show any relevant signal match.

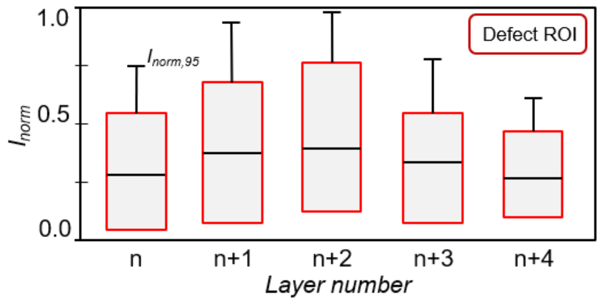

Figure 3. Boxplot of normalized photodiode intensity *(I_{norm})* in the region of interest (Defect ROI) containing the defect of Figure 2a.

4. Conclusions and future work

This study contributed towards advancing high-speed Laser Powder Bed Fusion technology. It achieved this by leveraging the valuable insights gained from implementing a methodology that enables accurate comparison between photodiode monitoring data and internal defects measured by X-ray CT. Results showed how pores located at the intersection of the hull and bulk strategy and with an equivalent diameter equal to or greater than 150 µm can be successfully identified by monitoring the photodiode data throughout several layers. On the contrary, although some spatter-related porosities were present in the hull-bulk samples, photodiode data did not show any clear signature in the corresponding regions of interest. This aspect will be better investigated in future experiments since the hull-bulk method - which was proposed as an effective trade-off between production time and mechanical properties [6] - might further benefit from the capability of grasping defects formation in real time. Given that off-axis long-exposure monitoring was shown to be effective for spatters detection [4, 5], combining multiple sensors is suggested to provide more comprehensive information regarding the different defect categories.

Acknowledgements

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