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In-situ Monitoring of Geometric Accuracy in Laser Powder Bed Fusion processes

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Abstract
The increasing interest for metal additive manufacturing (AM) technologies in highly regulated sectors like aerospace and healthcare imposes the need to achieve challenging part and process qualification requirements. Powder bed fusion processes represent the family of AM processes that provides the highest accuracy and resolution performances. However, several source of instability may yield geometrical distortions that shall be detected as soon as possible. This paper presents a study for in-situ identification of geometrical defects via high-resolution imaging of each layer. It allows comparing the geometry observed via on-line image segmentation with the nominal one for a quick detection of major departures. The calibration of the sensing equipment together with the repeatability and reproducibility (R&R) analysis of image sequences gathered in-situ is discussed, to highlight the possibility of using this tool for reliable in-situ measurements and to reduce the need for expensive and complicated post-process inpections.

Additive Manufacturing; in-situ monitoring; geometric accuracy; machine vision.

1. Introduction

The aerospace and the healthcare sectors are pulling the industrial development of metal additive manufacturing (AM) technologies for the fabrication of parts characterized by complex shapes, internal channels, functional surface patterns, trabecular structures for weight reduction, etc. However, they represent two highly regulated sectors where part and process qualification represent a challenging issue. As a matter of fact, various sources of process instability may lead to non acceptable scrap fractions. Typical defects include internal and surface porosity, cracks and delaminations, residual stresses, dimensional and geometrical distortions, impurities and deviations from the expected microstructure [1-3]. Because of this, most AM system developers have been integrating sensors for in-situ data acquisition, with a particular focus on machine vision equipment [1-3]. This makes the acquisition of high-resolution images of the powder bed on a layer-by-layer basis an easy task. However, what is still lacking in industry, is the availability of in-situ monitoring tools able to process those image sequences in-line and automatically determine if the process is in-control or not. This study presents a method for in-situ detection of geometrical defects based on coupling in-line image processing and segmentation algorithms with a statistical process monitoring approach to identify departures between the observed pattern and the nominal one. The method is applied to laser powder bed fusion (LPBF) processes, that represent the family of AM processes where the highest accuracy and resolution can be potentially achieved.

The study presents the proposed methodology for the in-line identification of deviations from a nominal slice shape. A repeatability and reproducibility (R&R) study is presented to highlight the actual in-situ measurement performances that can be achieved and to determine to what extent such in-situ measurements may reduce the need for conventional post-process inspections.

Section 2 briefly reviews the state of the art on in-situ monitoring of geometrical errors in LPBF. Section 3 briefly introduces the main building blocks of the proposed approach. Section 4 concludes the extended abstract.

2. State of the art

Both dimensional and geometrical defects were reported in the LPBF literature. Regarding dimensional errors, both shrinkage and over-sizing may occur [4 – 5]. In addition, different kinds of warpings were discussed by [5 – 6]. As an example, the curling phenomenon is a typical defect that leads to a combination of shrinking and warping that produces a curved profile of down-facing surfaces intended to be flat. Another kind of geometrical distortion is related to the formation of super-elevated edges [7- 8], i.e., elevated ridges of the solidified material at the edges of the successive layers. This defect affects both the surface topology and the dimensional accuracy of the part. Moreover, it may interfere with the recoating system, increasing its wear and worsening the powder bed uniformity. Other distortions affect critical features like thin walls, overhang surfaces and acute corners [9 – 10]. In those regions, the melt pool is largely surrounded by loose powder, which has a lower conductivity of the solid material. The diminished heat flux yields local over-heating phenomena that may deteriorate the geometric accuracy.

[11] presented a method for image-based 3D reconstruction of builds via image segmentation and slice edge detection. The method can be used to localize geometrical defects within the part, but also to detect powder ben inhomogeneities. Other studies [8 – 9] proposed image segmentation tools fot the detection and spatial localization of super-elevated edges. Similar tools have been recently implemented by some LPBF system developers. As an example, [12] presented an in-situ monitoring equipment (based on a high resolution CMOS camera) commercialized by EOS that allows performing a so-called "optical tomography" of produced parts. The method is

suitable for 3D geometric reconstruction and spatial localization of defects. Monitoring solutions for powder bed monitoring were developed by SLM Solutions as well (SLM Solutions, 2016). Their powder bed monitoring system is able to detect non-homogeneous depositions and automatically activate new recoating operations.

The main limitations of the methods for in-situ geometrical defect detection presented in the literature can be summarized as follows:

- The studies are mainly aimed at evaluating the feasibility of the in-situ measurements, without a formal characterization of the measuring tool performances;
- There is a lack of comparison analysis against benchmark measurements;
- There is also a lack of statistical monitoring tools for the design of automatic alarm rules to be implemented in-line.

The proposed study aims at addressing all these issues.

3. Proposed methodology

The proposed approach consists of the following steps: 1) acquisition of high-resolution images of each layer, both before and after the laser scan, 2) pre-processing and segmentation of the image to determine the contour of the scanned slice in each layer, 3) registration and matching analysis between the in-situ determined contour of the slice and the nominal shape from the sliced CAD model, 4) estimation of a “deviation index”, used to quantify to what extent the oberved shape deviates from the nominal one. As an example, Fig. 1 (top panel) shows the CAD model of an aerospace component that was fabricated via LPBF on a Renishaw SLM250 system with maraging steel powder. Fig. 1 (bottom panel) shows a detail of a defect in the as-built part, corresponding to a severe delamination caused by strong residual stresses originated during the LPBF process.

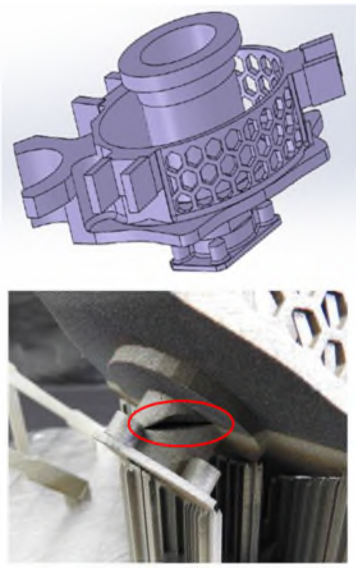

Figure 1. Top panel: CAD model of an aerospace part produced via LPBF; bottom panel: example of local defect in the as-built part

The proposed approach for in-situ comparison between the observed geometry and the nominal one was applied to the production of the part shown in Fig. 1. Fig. 2 shows an example of such comparison in correspondence of one layer where the defect started to be visible. The red contour corresponds to the nominal shape, whereas the white area corresponds to the filled contour resulting from in-situ edge detection.

Figure 2. Comparison between nominal shape (red contour) and observed geometry for local defect detection

Fig. 2 shows that the comparison between the two shapes allows one to detect an anomalous deviation (black gap), where the delamination occurred.

4. Conclusion

This study will describe the details of the proposed approach and will present an experimental study aimed at determining the sensitivity of in-situ measurement performances on different process conditions, e.g., the scan orientation in each layer, the effects of the illumination and other geometry-dependent effects. An R&R study will be carried out to characterize the suitability of the method for in-line geometrical qualification and for the reduction of the need for long and expensive post-process quality inspections.

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