Additive Manufacturing Letters 3 (2022) 100048

Contents lists available at ScienceDirect

Additive Manufacturing Letters

journal homepage: www.elsevier.com/locate/addlet

The intelligent recoater: A new solution for in-situ monitoring of geometric and surface defects in powder bed fusion

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ARTICLE INFO

Keywords:
Powder bed fusion
Process monitoring
Surface topography
Contact image sensor

ABSTRACT

Powder bed homogeneity, contaminations, and printed surface quality are crucial in powder bed-based AM processes to obtain a defect-free part, but the scale at which these defects are seen is not compatible with the resolution of current industrial image-based monitoring solutions. In this work, we explore the implementation of an optical scanner in an industrial laser powder bed fusion (L-PBF) machine to detect powder bed and part-related defects. The sensor is mounted ”parasitically” on the recoater and exploits its movement to scan across the build platform before and after powder deposition to obtain high-resolution images. The acquisition seamlessly integrates with the process, without delaying the production as the acquisition occurs in parallel with the new layer deposition. The system was used to monitor test builds as well as longer builds (1000 + layers) to prove its robustness to the challenging L-PBF chamber environment. The in-situ powder bed images of the new monitoring system were compared to the acquisitions of a standard external camera setup. The improved image quality and resolution of the new system were demonstrated on both large-scale (> 1 mm) and small-scale features. The new system proved to be capable of capturing printed surface topography anomalies and powder bed contaminations (< 100 μm), opening a whole new range of possibilities for detecting small-scale defects via in-situ monitoring.

1. Introduction

One of the most widespread additive manufacturing (AM) technologies is powder bed fusion, especially its laser-based version (L-PBF). Some of the reasons for its success are (i) the ability to produce fully-functional metal parts, (ii) the design flexibility, (iii) the wide range of available materials. However, these advantages come at the cost of high defect rate, low repeatability, and new challenges for part qualification. The inherent complexity of PBF productions, which is typically one-of-a-kind, often pushes the process at its limits and creates the conditions for increased defect formation. This contributes to the variability in the final mechanical properties of the part due to stochastic formation of defects (e.g., porosity, inclusions). For this reason, great attention is put on the qualification of parts, especially because the industries where L-PBF is most employed (i.e., aerospace and biomedical) are subject to stringent quality requirements. However, the geometrical complexity (e.g., abrupt thickness change, internal surfaces) creates new challenges for non-destructive inspection (NDI) of parts, and researchers from both industry and academia have been working on the development of novel solutions for part qualification. To this regard, many have started looking into process monitoring as a way to support the production and qualification of AM parts [1,2]. In principle, the layer-by-layer manufacturing scheme of L-PBF allows to monitor the part as it gets built by acquiring process and part-related characteristics, a.k.a. process signatures. These can range from very fast process dynamics, e.g. melt pool monitoring, to layer-wise imaging of the printed slice and powder bed.

Different process signatures are employed depending on the specific target defect, but, despite providing useful insights about the process, not all can be implemented outside of a laboratory environment. This can be due to several factors, for example, the generation of large amounts of data, the need of dedicated setups, or other requirements which make some monitoring techniques impractical for industrial use.

Among all available monitoring techniques, layer-wise powder bed imaging is the most diffused at industrial level, and it is currently available for most modern industrial AM machines. Despite offering a very simple data set (usually 2 images per layer, before and after powder spreading), it is particularly useful for detecting macroscopic deviations and defects that are either part-related (i.e., super-elevated edges) or powder bed-related (i.e., recoater hopping, streaking, incomplete spreading). While its implementation is the most practical for industrial use, it also has several limitations regarding:

- *Resolution*: depending on the desired field of view (i.e. build platform size), resolution can range between 30 μm/px for smaller machines and build platforms (∅≈ 50 mm), and > 200 μm/px for larger ones (∅≈ 500 mm). The direct consequence of this is the minimum feature size that can be detected with the monitoring setup.

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https://doi.org/10.1016/j.addlet.2022.100048
Received 21 March 2022; Received in revised form 20 April 2022; Accepted 21 April 2022

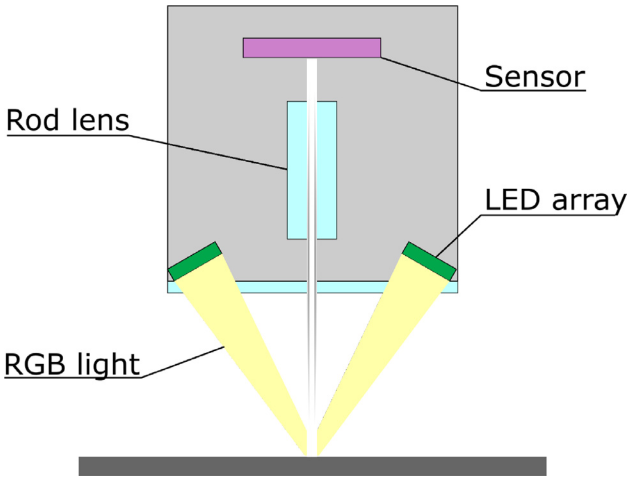

Fig. 1. Built-in RGB light arrays.

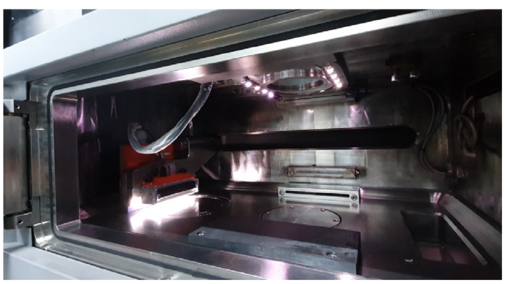

Fig. 2. Build chamber.

- *Lighting*: proper illumination of the target is crucial for getting good quality images. However, the lighting conditions in the build chamber are often unideal. The scene often tends to suffer from a non-homogeneous lighting condition, especially in larger build platforms. In addition, the printed metal parts reflect some of the light depending on scan strategy orientation and resulting surface topography.
- *Perspective*: since powder bed cameras are placed off-axis, perspective error are expected. This distortion modifies the true geometry of the scene and needs to be corrected. Image warping is usually applied to eliminate the perspective error but this manipulation stretches the image, adding noise and artifacts.

These three aspects have a strong influence on the final image quality, and, consequently, on the information that can be extracted from it for defect detection.

Most works dealing with process monitoring via powder bed imaging demonstrate the detectability of macroscopic powder bed defects [3,4] and deviations from the nominal slice geometry [5]. However, the printed surface and powder bed carry a lot more information about process defects when looked more closely. For example, irregularities in the printed surface topography can indicate the occurrence of out-of-control melting conditions [6], and the presence of powder bed contaminations were found to correlate with the formation of lack-of-fusion [7]. Standard off-axis cameras are not sufficient to detect these defects. Higher resolution sensors must be employed to reconstruct surface topography and other small features.

Zhang et al. [8] used an off-axis camera to reconstruct surface topography via fringe projection. The camera had a very small field of view (28×15 mm^2) to obtain the high resolution required. They successfully demonstrated the capabilities of the method at reconstructing printed surface texture and powder bed contaminations, but this monitoring setup is not compatible with industrial machines and processes due to the limited field of view, and the non-negligible acquisition time it adds to the process.

Recently, new sensor architectures have been developed to avoid the field of view limitations while still retaining a resolution which can capture small scale features. Tan Phuc and Seita [9] first started working on implementing a flatbed office scanner in a powder recoating test rig for high-resolution powder bed imaging. The system exploits the recoating mechanism to scan the 1D sensor across the powder bed and obtain a final 2D image which covers the whole build space while retaining a very high resolution (up to 5.3 μm/px at 4800 dpi). They demonstrated the capability of the system of resolving single grains of powder and detecting spreading defects by leveraging the shallow depth of field of the sensor and evaluating the out-of-focus.

A similar recoater-based architecture was developed by Fischer et al. [10] using a high-resolution line camera. The performance of this method for layer-wise powder bed imaging is demonstrated by comparing the images to ex-situ surface maps. The researchers do not report any additional time for the acquisition, but this monitoring setup would be extremely challenging to implement in industrial L-PBF machines due to:

- *Space limitations*: the line camera needs to be paired with a lens and this system requires plenty of free space inside the build chamber. In addition, compared to the flatbed scanner solution, it requires a large working distance (> 70 mm) between the lens and the target, which further increases the size of the setup.
- *Scalability issues*: the line camera setup is hardly scalable without compromising the resolution and increasing the working distance. This could be solved using a multi-camera setup, but it would multiply the already high setup cost and the required space.

Following the seminal work of Tan Phuc and Seita [9], in this study we present the implementation of a recoater-based image scanner in an industrial L-PBF machine. Unlike the other high-resolution monitoring setups that have been discussed previously, the system implemented in this work can be virtually fitted in any existing industrial machine, and can be scaled thanks to the availability of larger sensors that increase the FOV without compromising the resolution. The advantages offered by the new solution over the other industry-standard systems are shown with a side-by-side comparison between the acquisitions of the new system and the ones of a traditional camera-based powder bed monitoring setup. Real-world case scenarios were chosen for the comparison and to demonstrate the performance of the new setup at detecting both small-scale and large-scale defects on the printed surface and the powder bed. Ex-situ characterization was used for validating the results.

2. Materials and methods

2.1. In-situ monitoring equipment

The optical scanner selected for this new monitoring setup is a contact image sensor (CIS) made by WHEC. The scanner system is composed by the CIS itself and an A/D converter and it offers a high optical resolution of 21 μm/px (1200 dpi) combined with a field of view that matches the size of the build platform. Thanks to its configuration and recoater-based implementation in the L-PBF machine, the industrial optical scanner eliminates the typical sources of image deterioration in traditional off-axis imaging systems. Besides combining a high-resolution with a large field of view, the industrial scanner integrates two internal RGB LED arrays that illuminate the scene co-axially (Fig. 1). Since the light moves together with the sensor while scanning, the resulting image can benefit from homogeneous lighting conditions across the whole image. The right-angle positioning of the sensor offers another advantage over traditional off-axis camera, which is the lack of perspective errors during acquisition, and the ability to capture color-accurate images of the powder bed and printed surface. Color images are obtained from the

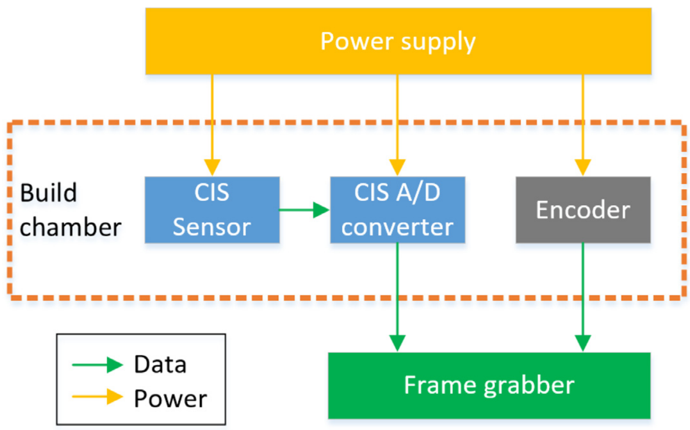

Fig. 3. Monitoring system scheme.

combination of single lines captured with red, green and blue light illumination. This is made possible by the fast switching RGB LED arrays mounted on the CIS, which allow for sequential acquisition of lines with different illumination configurations.

All the advantages of this monitoring system come with a few implementation complexities. Being a 1D line sensor, the CIS needs to be scanned across the build platform to reconstruct a 2D image. In principle, continuous acquisition is possible, but the potential variations in recoating speed during powder spreading may result in unacceptable image warping. For this reason, the scanner requires a precise and repeatable position-based synchronization of the acquisition. This can be achieved by either probing the position signal from the encoder of the recoater motor or by installing an external encoder alongside the scanner. For this work, due to the closed environment of commercial machines, the external encoder solution was implemented, thus increasing the overall complexity of the system. The incremental linear encoder used in this work is the Elgo GSI2 and has a resolution of 1 μm. The resolution was selected to be a submultiple of the optical resolution of the CIS to control the acquisition frequency and maintain a 1:1 aspect ratio of the pixels.

The CIS itself needs to be mounted very close to the target surface (14.8 mm) due to its short focal distance. The direct consequence of this is the shallow depth of field (DOF) of the CIS rod lens, which translates into a very small depth of the scene appearing in focus. To ensure precise positioning and focusing of the instrument, a linear translation stage was mounted between the recoater and the CIS.

The scanner and the encoder are directly connected to a Teledyne Dalsa frame grabber (Xtium-CL MX4) to transfer image data and synchronize the position with the acquisition. A C++ routine was developed using the Sapera LT SDK to automatically acquire the images for each layer.

2.2. L-PBF machine and monitoring setup integration

The industrial L-PBF machine on which the monitoring system was installed is the 3D-NT made by Prima Industrie. The system is equipped with a 500W laser that can operate in either continuous or pulsed wave mode, and a 150 mm build platform. The architecture of the machine is one of the most common in modern L-PBF machines. It comprises a wide build chamber with two motor-actuated cylinders that host the powder reservoir and the build platform respectively (Fig. 2).

The biggest challenge of integrating a recoater-based imaging system into a commercial L-PBF machine is appropriate cable routing. The scheme of Fig. 3 shows all the elements of the monitoring system and highlights all the cables that need to travel across the build chamber. To minimize potential air leaks, all power cables and data cables were grouped into one and routed through a cable gland mounted in place of the off-axis camera window. To ensure safety, all electrical connections

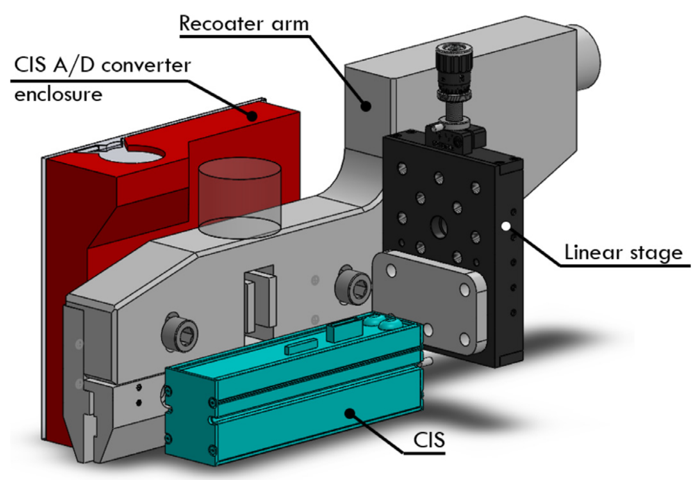

Fig. 4. Recoater arm with CIS.

are certified IP6x for dust protection, and custom 3D printed enclosures were designed to minimize powder contamination.

The removable part of the recoater arm was adapted to mount all the necessary monitoring equipment (Fig. 4). The linear encoder was placed in the back of the machine and connected to the recoater translation system. Since the CIS is positioned ≈ 40 mm in front of the recoater, the system can acquire the build space area before and after spreading in just one recoating cycle. With this setup, no additional acquisition times are required because the two acquisitions (before and after new powder layer spreading) occur in parallel with the recoating process.

2.3. Case studies

A few real-world case studies were selected to demonstrate the capabilities of this new monitoring system:

- Small-scale features (< 1 mm):
  - Printed features (vertical pins, ∅0.3 and 0.6 mm)
  - Printed surface topography (bulk and overhanging sections)
  - Powder bed contaminations
- Large-scale defects (> 1 mm):
  - Powder bed inhomogeneity (incomplete spreading)
  - Part warping (residual stress induced out-of-plane deformation)

All scanner acquisitions were compared against the images obtained from a standard high-resolution off-axis camera (IDS UI-5490SE-C-HQ with a 25 mm lens) placed outside of the build chamber. Some of the images were also compared with surface topography and part warping

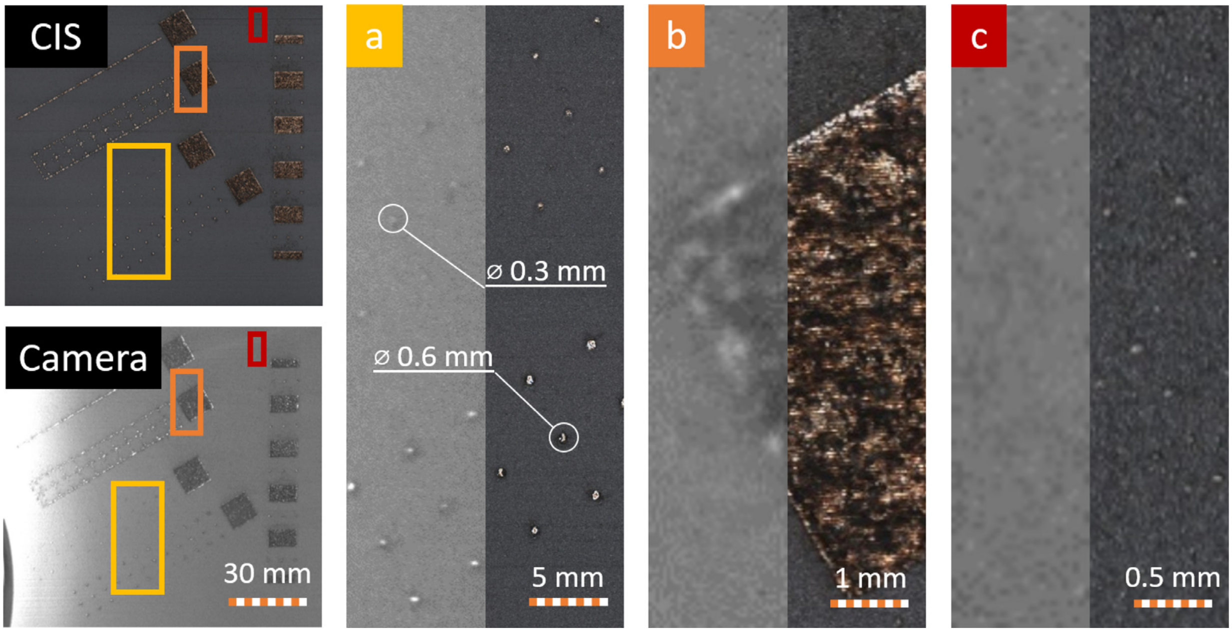

Fig. 5. Side-by-side comparison of powder bed images details taken with the CIS (on the right) and the off-axis camera (on the left). The colored boxes on the two full original images on the left highlight the position of the close-ups shown in the a-c subplots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Default process parameters for AlSi10Mg.

Laser parameters		
Laser mode	Continuous wave	
Power	200	W
Power (DS)	150	W
Slicing parameters		
Layer thickness	25	µm
Hatching parameters		
Number of borders	0	-
Hatch distance	90	µm
Rotation btw. layers	67	degrees
Pattern	Meander	
Scan speed	1000	mm/s
Up-skin parameters		
Up-skin	Disabled	
Down-skin parameters		
Down-skin	Enabled	
Number of layers	2	-
Replace regular hatches	Yes	
Number of exposures	1	-
Hatch distance (DS)	60	µm
Offset to volume area	-50	µm
Pattern	Meander	
Scan speed	1250	mm/s

measurements done ex-situ using a Focus Variation Microscope (Alicona InfiniteFocus, 10x magnification).

The parts were printed using an aluminum alloy powder (Carpenter's AlSi10Mg, size distribution 15–45 µm) and default process parameters (Table 1).

3. Results and discussion

3.1. Small-scale features

Small-scale features include sub-mm sections that have been purposedly printed to demonstrate the performance of the new monitoring system, and small process-related characteristics or by-products that develop during the L-PBF process. The full image of the build space taken with the optical scanner and the off-axis external camera are shown on the left side of Fig. 5.

The subplots 5 a–c offer a more close-up, side-by-side comparison of the small-scale details that can be found in the original images, and each of them highlights the potential of the CIS scanner over the current standard off-axis imaging.

Figure 5 a shows a close-up image of small pins that were included in the test print. Two clusters of pins of different size (⌀0.3 and 0.6 mm) were manufactured. While the 0.6 mm pins can be clearly observed in both acquisitions, the smaller 0.3 mm pins are barely visible in the off-axis camera image. The higher resolution of the CIS-based setup offers a greater detail on small printed features, and a clearer distinction between the powder background and the printed metal. This effect is even more visible in Fig. 5b, which shows a portion of a larger (10×10 mm^2) printed surface. In the CIS image, the edges of the slice are clearly distinguishable from the powder background. On the other hand, in the camera image, the edges of the printed surface blend with the surrounding powder. The high-resolution and sharp edges of the CIS images would greatly benefit in-situ metrology applications [5], which strongly rely on image segmentation and edge detection accuracy to improve the final reconstruction quality.

CIS imaging also enables direct powder bed inspection for detecting contaminations. Figure 5c clearly shows the presence of process-induced contaminations in the powder bed, which appear as approximately spherical powder particles which are larger in size than nominal (≈ 80–100 µm in diameter).

CIS imaging can also capture topographic characteristics of the printed surface. For example, laser hatch lines are visible on the printed surface of Fig. 5b. However, when dealing with more critical process conditions, a more complex surface topography can be expected. To study realistic and process-induced topographical defects with the new monitoring setup, a bridge sample was printed. The specimen comprises a down-facing 10×10 mm^2 section supported at mid-plane. The printing of the bridge sample was interrupted 3 layers after the start of the overhang section to allow for ex-situ characterization of the surface topography. Printing down-facing surfaces represents one of the main challenges of L-PBF due to the loose powder substrate. This condition is critical for the process and it often results in a higher defect concentration near those regions.

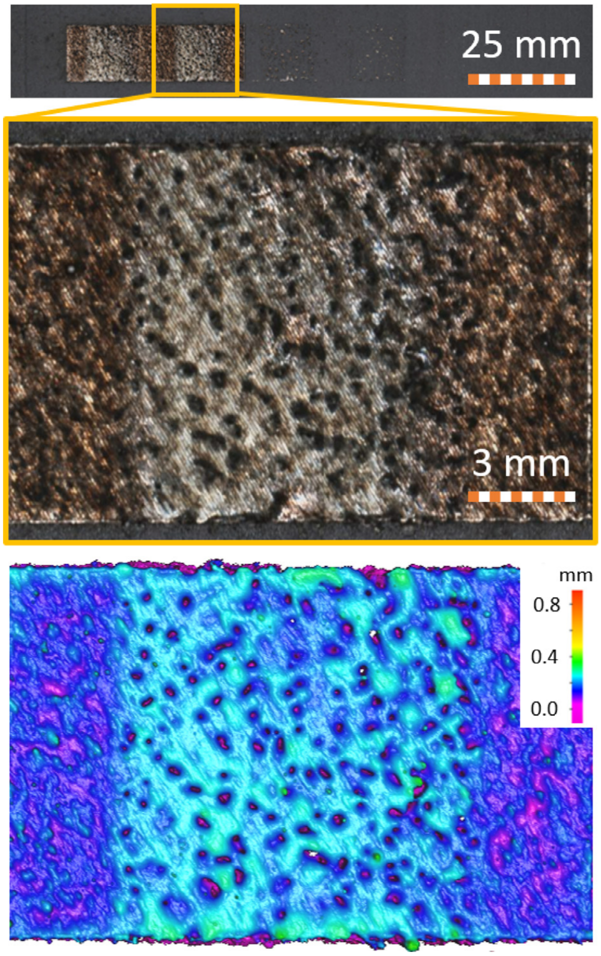

Fig. 6. Surface topography of the overhanging section of the bridge specimen after 3 layer.

From Fig. 6 it is possible to see that the CIS acquisition perfectly matches the surface map obtained ex-situ via Focus Variation Microscopy. A very high concentration of open pores can be found on the top surface of the overhang section, which is the direct consequence of printing a section directly over a loose powder substrate.

3.2. Large-scale features

Large-scale features are the macroscopic process deviations that can be observed during a L-PBF process. These features include deviations that appear ”out-of-plane” with respect to the flat powder bed, and that are either related to the part (i.e., warping and super-elevated edges, swelling) or the powder bed deposition (i.e., recoater hopping/streaking, incomplete spreading). For these types of defect, off-axis cameras have a slight advantage over the optical scanner. The inclined position of the camera and the fixed lighting source, which casts shadows near the out-of-plane defects, help with their detection in the image. On the other hand, the moving lighting system and the right-angled orientation make the scanner potentially less sensitive to the presence of out-of-plane defects. However, as discussed by Tan Phuc and Seita [9], the shallow depth of field (DOF) of the CIS can be exploited to detect out-of-plane defects, which will appear out-of-focus in the image.

Figure 7 shows the results that can be obtained by applying a focus measurement operator to detect out-of-plane defects in the powder bed (incomplete spreading) and the part (warping). Subplots a-b of Fig. 7 show an extract of the images acquired with the CIS (7 a) and the external camera (7 b). With the camera image, the out-of-plane defects are easier to spot. However, by applying a simple focus measurement operator (FMO), the out-of-plane defects can be clearly highlighted in the image. For further validation, the height-map of the warped part was measured using ex-situ equipment. The comparison between the FMO image (Fig. 7c) and the height-map measurement (Fig. 7d) confirms a qualitative agreement which could be leveraged to indirectly estimate the severity of the out-of-plane defect.

A side effect of having a recoater-mounted sensor is that the acquisition is sensitive to potential disturbances in the recoater motion. This effect may occur when the parts are affected by excessive warping and they start colliding with the recoater blade, as it was observed in one of the test prints. A part with weak supports warped significantly during the process and started hitting the recoater blade during each new layer deposition. The collision and the associated vibrations had a visible effect in the line-by-line image acquisition process. Specifically, when the collision happens, the image warps for a few scan lines until the recoater passes the obstacle and recovers its normal motion (Fig. 8). Due to the 40 mm offset between the CIS and the recoater blade, the distortion in the image occurs 40 mm after scanning the super-elevated edge that caused the collision. This makes it easy to locate the position of the most process-critical defects in the image.

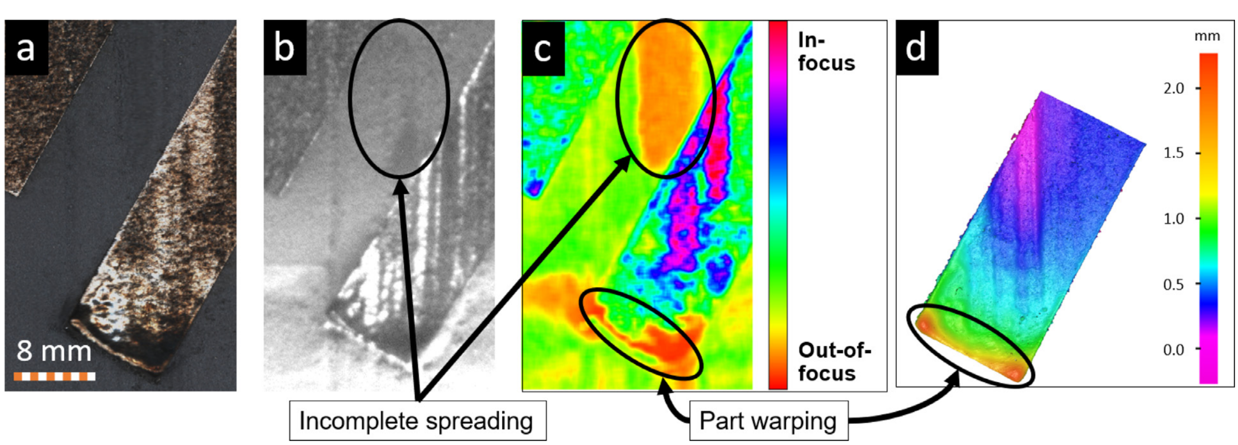

Fig. 7. Examples of out-of-plane defects taken with the CIS scanner (a) and the external camera (b). (c) shows the result of applying a focus measurement operator to the original scanner image. In (d), the height-map of a warped part obtained with ex-situ measurements is displayed.

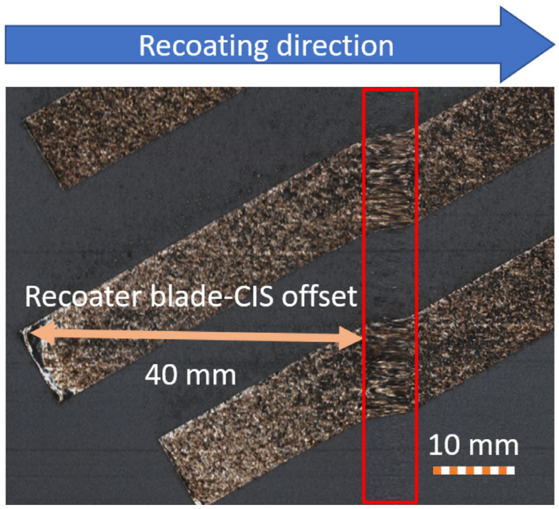

Fig. 8. Effect of recoater collision on the CIS image. The red box highlights the collision-induced distortion in the CIS image. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

In this first work we demonstrated that it is possible to integrate a recoater-mounted imaging sensor in a commercial L-PBF system. The high-resolution and high field of view offered by the CIS scanner significantly improves the current layer imaging quality standards at no additional cost in terms of acquisition time. This has an obvious impact on in-situ macroscopic defect detection and geometry reconstruction accuracy, and, most importantly, it opens a whole new range of in-situ monitoring possibilities.

The performance of the sensor allowed to start exploring new characteristics that influence the process on a smaller scale, and improved the detection of large-scale defects. These include part and process-related features such as:

- *Large deformations and powder inhomogeneity*. Part warping and incomplete spreading not only were clearly identified but also qualitatively evaluated thanks to the shallow depth of field of the CIS.
- *Small geometrical features*. The detection of small geometrical features was demonstrated thanks to the overall improved edge reconstruction capabilities that will enable more accurate in-situ geometry monitoring.
- *Surface topography and open pores*. Surface topography, up to single laser hatch lines, can be closely monitored with this system. This also includes the detection of surface topography deviations and open pores formation when the process is facing sub-optimal process conditions, i.e. when printing over loose powder.
- *Powder contaminations and other new process signatures*. The ability to detect features that develop from the interaction between the powder and the laser, i.e. powder bed contamination, was briefly discussed in this preliminary study. However, several other process characteristics could be detected thanks to the high-resolution and the true color images that are exclusive to the CIS (e.g., discoloration, burned areas, oxidized spots).

Future work will be devoted to the development of new in-situ monitoring strategies that take advantage of the resolution and the colored images of the new sensor to study new process signatures and correlate them with final part quality characteristics.

Funding

This project was partially funded by the:

- European Space Agency (ESA Contract No. 4000125528/18/NL/MH/mg) and RUAG in the frame of Matteo Bugatti's co-sponsored Ph.D.
- IAMSPACE Project – Italy for Additive Manufacturing in SPACE, funded by ESA in the framework of agreement AO10042 – "Preparation of Enabling Space Technologies and Building Blocks: AM process Monitoring and Structural Integrity".

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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