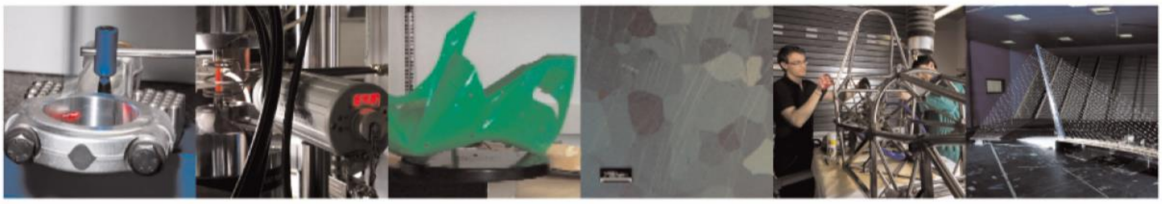

Penelope: A Novel Prototype for In Situ Defect Removal in LPBF

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PENELOPE: A NOVEL PROTOTYPE FOR IN-SITU DEFECT REMOVAL IN LPBF

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Abstract

A new Laser Powder Bed Fusion (LPBF) prototype for in-situ monitoring of defects and in-situ and in-line flaw removal has been developed and patented in Politecnico di Milano (Italy). This prototype allows one to identify a defective layer thanks to an innovative in-situ monitoring approach that combines image and video-image data in the visible and infrared ranges. When the alarm is issued, the layer containing the defect is removed in-situ and in-line, thanks to a novel self-repairing system acting as a grinder on the powder bed. After this removal step, the following layers are additively produced starting from the healed height.

By comparing specimens obtained with and without the intermediate layer removal, this preliminary study aims to investigating the feasibility of the methodology, showing that no discontinuity is introduced in the part by the novel in-line removal operation. This solution is conceived to enable novel zero-defect and first-time-right capabilities in additive manufacturing.

Introduction

In the last decade, Laser Powder Bed Fusion (LPBF) technology has gained an increasing attention from the industry for the capability of producing complex-shaped and lightweight parts and, at the same time, to reduce the material requirement and the time-to-market. Its adoption in different industrial sectors, like aerospace and healthcare, tooling and molding, automotive and creative industry [1-3] is still increasing, paving the way for a future series production.

Although many would consider LPBF a relatively mature technology, the low process stability and repeatability still represent a limit that dramatically reduces the spectrum of potential applications. This is a weakness point particularly for strongly regulated sectors, such as the healthcare and the aerospace, where a high degree of part quality assurance is required. These factors, together with the difficulties related to product qualification, pushed LPBF system developers and the academic community to direct their research efforts towards in-situ measurements and monitoring to inline qualify both the part and the process [1,2].

The layer-wise nature of L-PBF not only allows inline measurements, but also makes possible the implementation of procedures to remove defects during the process and to restore the part once a failure is detected.

One motivating example is shown in Fig.1. This case study refers to the re-design of a component for the space industry. Fig.1a shows an undesired super-elevated area occurred at around a half of the process. This resulted in an error in powder recoating in the following layers, which cannot be solved by consecutive powder recoating. This caused an evident delamination in the final part for the further deterioration linked to thermal stresses (Fig. 1d). Fig. 1c shows that by combining images taken before and after the laser scanning (Fig. 1a and Fig. 1b), it would have been possible to detect a mismatch between in-situ detected slice boundaries and the nominal slice shape and thus, identifying the onset of the defect. In this case, an in-line defect correction could, in principle, avoid the production of a scrap with consequent savings in terms of time and wastes.

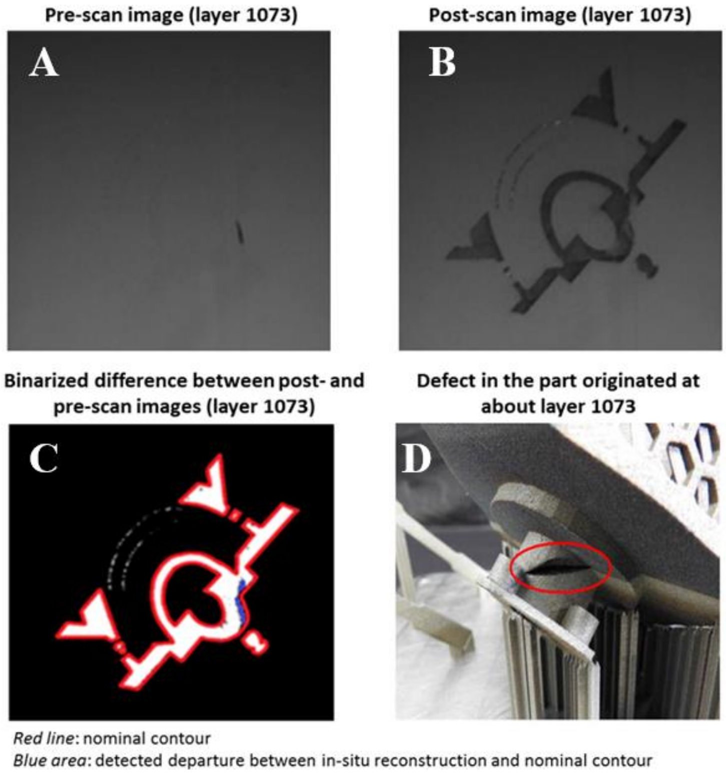

Fig. 1 a) powder bed before layer scanning. It is evident a deposition flaw in the centre **b)** powder bed after layer scanning **c)** comparison between actual layer borders and nominal shape. The blue area highlights the mismatch between them **d)** Lateral view of the final part. A geometrical deviation is evident in correspondence to the defective layers. Reprinted with permission from reference [4]

Nevertheless, in the existing industrial machines, the layer-wise data are used just for visualization purposes and no automated approaches have been implemented to signal the onset of a defect, apart from few seminal and simplified tools. Moreover, the only possible action that consists of aborting the process if something goes wrong, wasting the part and re-starting the process with different process parameters or different job design settings. Few seminal studies investigated either the possibility to prevent defects by means of closed-loop control strategies [5] or methods to mitigate porosity and residual stresses by adopting layer re-melting [6-9]. However, these studies are at the early stage and no commercial LPBF system already implemented any of these solutions.

This paper presents a novel LPBF prototype, called *Penelope*, characterized by an open architecture and multiple in-situ sensors, which embeds a novel in-line defect-repairing system. *Penelope* indeed combines a multi-sensor monitoring architecture with a hybrid apparatus for in-line defect removal. The defect removal system consists of a surface grinding wheel mounted on a linear axis. This system is activated to get rid of layers where defects were identified. Once the layer removal operations come to the end, the system carries out the previously interrupted LPBF process, possibly with modified process parameters to prevent from re-occurrence of the same defect. The paper also presents preliminary results to demonstrate that the defect removal process is feasible, and that it does not alter the process stability and part integrity.

This paper is organized in the following sections: Section 2 briefly reviews the state of the art on in-situ detection, mitigation and correction of defects; Section 3 presents the LPBF prototype system; Section 4 presents the preliminary results of experimental activities. Section 5 concludes the paper.

State-of-the-art

The increasing attention on in-situ sensing and monitoring has triggered not only the need of methodologies suitable to make sense of collected data, but also to use them to prevent and/or repair them by means of data-driven strategies. So far, three main streams of research have been implemented. The first is focused on real-time feedback control methods where in-situ measurements are used to implement a closed-loop control on process parameters. The second is aimed at reducing the occurrence of defects by applying superficial treatments through laser re-melting. Finally, the third approach makes use of subtractive manufacturing processes to delete defects once they have been detected.

In the first category, the very first seminal study was carried out by Craeghs, Bechmann, Berumen and Kruth [5]. They demonstrated that it is possible to adapt the laser power based on the measured melt pool emission, as a proxy of its area [5]. The results presented by these authors were tested on the production of overhang areas, showing the effectiveness of the method in producing the part without additional supports. A more recent study was presented by Renken, Von Freyberg, Schünemann, Pastors and Fischer [10], who presented the adopted monitoring strategy consisting in a cascade-control architecture divided in three levels. In the lowest level, data coming from a coaxial pyrometers and low coherence interferometer are used to estimate both the melt pool temperature and its depth. The parameters adjustment is performed thanks to an FPGA unit by considering the difference between the in-situ values and set points computed in the highest levels. Indeed, for each hatch, results coming from the lowest level are aggregated to compute the current track temperature profile and to determine the reference set points for the following track. The same mechanism is adopted at the highest level, where track data are further aggregated to create a slice temperature profile, which is exploited to determine the following layer set points. As the previous studies, a bridge shaped part was used to test the concept. The authors observed that the combination between feedback and feedforward control in this architecture achieves a lower standard deviation of the signal with respect to the adoption of a single approach. This paper showed that real-time feedback control in LPBF is possible with much higher scan speeds than previous seminal studies, but further research developments are needed to make this approach sufficiently robust for industrial implementation. Moreover, due to wide range of complex shapes and challenging materials in LPBF, feedback/feedforward control strategies may be not sufficient to guarantee defect-free parts.

Rather than changing process parameters via closed-loop adaptation, a second research stream investigate the mitigation and correction of defects thanks to laser in-situ treatments. So far, layer re-melting is the most investigated repairing solution to reduce internal porosity [6,7], surface roughness [8,9], local stress concentration and to improve microstructure characteristics [8]. Mireles, Ridwan, Morton, Hinojos and Wicker [6] artificially created seeded pores with by varying their size and shape. They showed that results in terms defects mitigation are comparable to post-process hipping treatment. [6] suggests also to couple this approach with closed-loop control strategy via thermal image acquisition, in order to apply laser re-melting only once a defect has been detected. The potential increase of production time due to layer re-melting was also discussed by Heeling and Wegener [9], who proposed a new machine configuration based on the use of a second laser sources with a larger beam diameter to heat the surrounding melt pool area.

The third approach consists of correcting the defect by combining additive and subtractive methods. Yasa, Kruth and Deckers [6] discussed the combination of LPBF and selective laser erosion to improve in-plane and out-of-plane quality characteristics and to increase the minimum process resolution. Although this approach was proposed to improve the layerwise surface properties, it can be used, in principle, to remove defective layers before re-starting the process. The approach proposed in this study follows a different perspective. It employs a surface grinding process to removes the last printed layer (or a few adjacent layers) where defects were detected.

Penelope: system configuration and methodology

Overview

The system here presented is a highly sensed LPBF prototype which combines the additive manufacturing paradigm with a subtractive system for defect deletion. The system includes four main modules, i.e. a build chamber, a gas recirculation system, a laser source and a laser scanner. Fig. 2 shows the overall system configuration and a detail of the mechanical structure within the build chamber.

Fig.2b shows the 3D CAD model of the mechanical structure within the build chamber. The powder is fed inside a powder hopper and it is spread on the build platform by means of a silicon rubber recoating blade, which can be moved on a linear axis. A vibrating blade allows the release of a defined quantity of metallic powder from the hopper. Finally, a surface grinding wheel installed into a grinding cart mounted on the same axis of the recoating system is aimed at performing layer deletion once a defect is identified. The whole chamber operates in an inert environment, filled with argon. The laser source consists of a IPG YLR-150/750-QCW-AC single mode fiber, a Ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser source (maximum power of 250 W and a wavelength of 1060 nm). This laser source can be set to operate both in continuous and pulsed mode with a pulsing frequency of up to 10 kHz and a tunable duty cycle.

The scan head control is managed by an Optoprim EC1000 controller, while the prototype control is based on an in-house produced controller managed through LabView custom programs.

Additional details about the in-situ sensing configuration and the in-line layer removal procedure are discussed in the two following sub-sections.

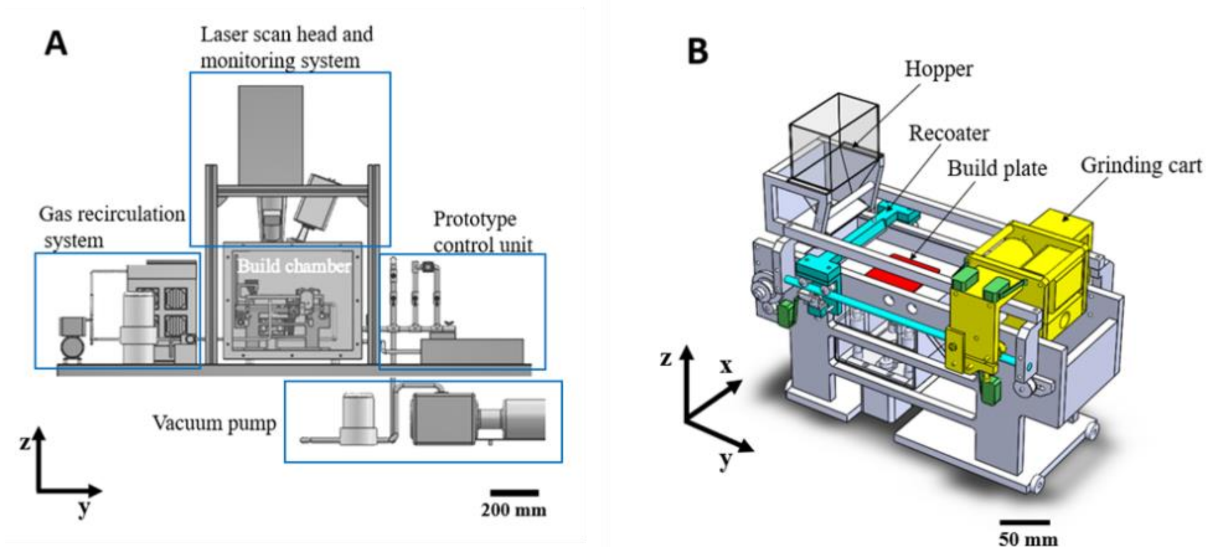

Fig. 2. a) front view of the whole prototypal system, with the division in sub-sections; **b)** CAD model of the mechanical components within the chamber

In-situ sensing

The prototype system enables the adoption of different monitoring strategies thanks to the complementary sensors installed in the system (Fig. 3). To acquire the in-situ images of the powder bed, before and after the laser scan, the prototype system is equipped with a high-resolution camera (10.5 Mpixels) with a 25 mm lens, which provides a spatial resolution of about 20 μm/pixel. 6 LED light stripes installed on the roof of the chamber are used to generate different lighting conditions (e.g. bright field, dark field or diffuse light) according to the specific measurement needs. It is also equipped with a high-speed camera (A I-SPEED 220, spatial resolution equal to 100 μm/pixel, maximum frame rate equal to 204 kHz) and a MWIR camera (FLIR X6900sc, 200 μm/pixel, maximum frame rate equal to 1004 Hz, spectral bandwidth between 3000 and 5000 nm, temperature between 300 and 1500 °C,). These cameras enable the study of different process signatures, such as process by-products [11, 12], hot and cold spot occurrences, local thermal gradients, etc. [13]. The choice of two wavelength ranges for the coaxial and off-axis infrared cameras comes from the different temporal resolution needs. Indeed, the coaxial melt pool monitoring requires a high acquisition rate (>10 – 20 kHz), which cannot be reached with the commercial medium/long infrared thermal cameras. These requirements can be fulfilled by means of a high-speed visible camera equipped with NIR bandpass filter. Besides, the off-axis monitoring does not impose a so stringent temporal resolution, thus a MWIR is employed to observe a wider temperature range with a relatively high acquisition rate.

Finally, a co-axial monitoring setup that includes a NIR camera with frame rate of up to 1 kHz for the characterization of melt pool completes the monitoring system.

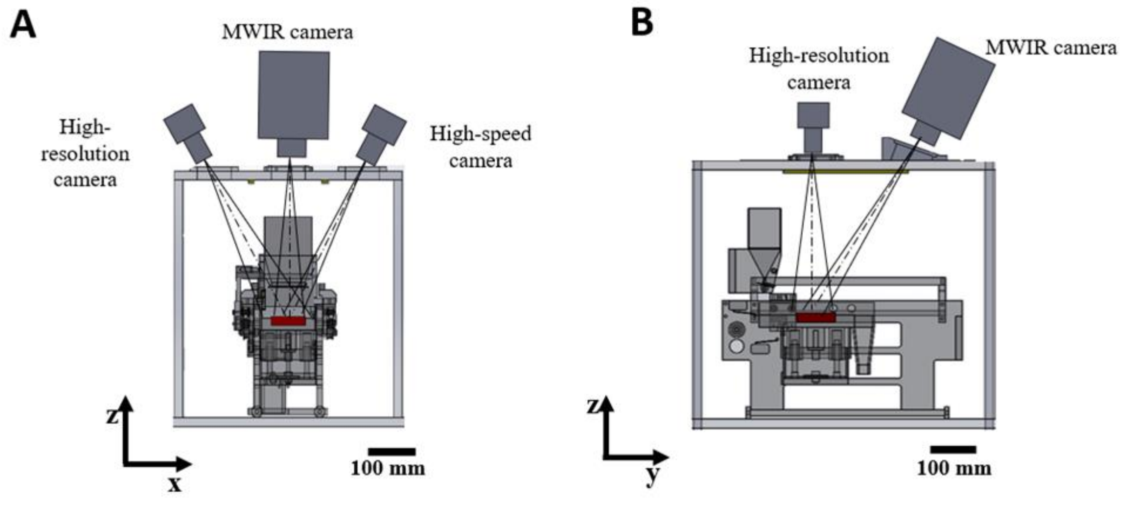

Fig. 3. Lateral **(a)** and front **(b)** views of the build chamber section with off-axis in-situ sensing equipment

In-situ defect removal

Once an in-pane or out-of-plane defect has been detected, the embedded layer removal system can be activated. Both the cart translation and wheel rotation speed can be set up to a maximum of respectively 30 mm/s and 7000 rpm. The procedure involves four main steps.

In the first step, after that the cart moves the grinding wheel above the build plate, the build top surface approaches the grinding wheel by translating along the z-direction from its starting position Z_{in} (i.e. the height of the last built layer), until it is in contact with the grinding wheel ($Z_{contact} = Z_{in} + \Delta h_1$, where Δh_1 is the distance between the top surface of the part and the grinding wheel). During this phase the translation along the z-axis is carried out with steps of 50 µm. A lateral camera with a field of view plane perpendicular to the powder bed (see Fig. 4) keep under control the distance between grinding wheel and top surface to interrupt the translation once the contact between the grinding wheel and the part is recorded.

Once the grinding wheel is in contact with the part, the grinding operation (i.e. the second procedure step) is activated. The grinding wheel performs multiple removal passes with constant depth of cut (usually between 10 and 20 µm) by simultaneously translating forward and back above the grinded surface and rotating at a given speed, until a target depth Δh_{rem} is removed. The value Δh_{rem} depends on the nature and the magnitude of the defect and can be determined by means of the monitoring system.

After the completion of the removal process, the third step is aimed at bringing the part at its initial position Z_{in} by lowering the build platform of Δh_1.

It is worth mentioning that the vibrations caused by the removal process (step 2), together with the undesired interaction between the grinding wheel and the surface of the powder bed, and the production of chips, may yield a contamination and a homogeneity alteration of the powder bed, which hinder the possibility to proceed with the LPBF process.

To restore it to the initial powder bed flatness, the step four is performed. It consists in iteratively depositing and spreading new powder beds by means of the recoater system, until the initial powder bed homogeneity is restored. This step also allows to bury the chips underneath the new powders layers, limiting the interaction between them and the powder bed and preserving the stability of the process. In order to verify the effectiveness of multiple powder recoating for powder bed homogenization the high-resolution camera is employed. After the end of the fourth step, the process starts again from the current layer with new process parameter (if necessary) to avoid the occurrence of the same defect.

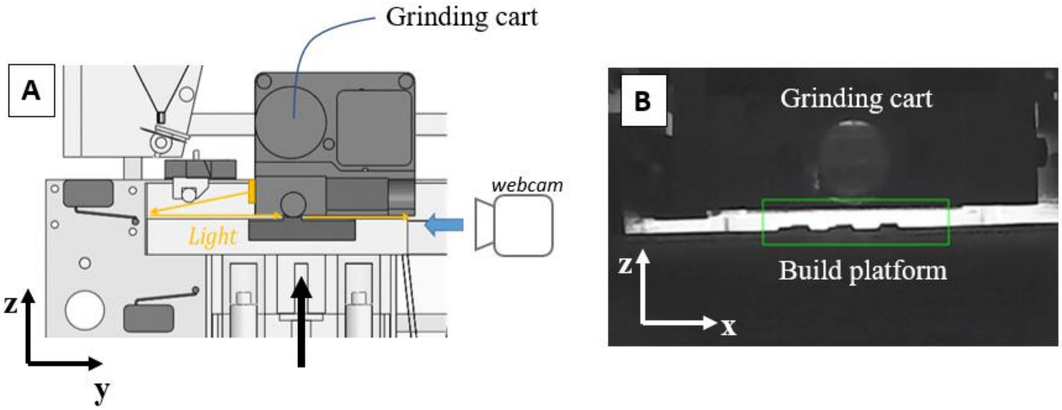

Fig. 4. a) lateral section of the prototype during the grinding process; **b)** Image acquired by the lateral camera

Preliminary experimental study

A proof-of-concept experiment was designed to determine the feasibility of the in-line layer removal. It was driven by the following research questions. First, this study tried to understand whether the removal system introduces any kind of discontinuity in the material, like porosity or lack of layers adhesion. Then, as the powder bed is altered by the removal process and contaminated by the resulting chips, the possibility to restore a contamination-free and uniform powder bed after the in-line layer removal is investigated. Finally, preliminary mechanical tests were performed to understand whether the grinding process significantly affects the mechanical properties.

For these purposes, two builds, each one containing three AISI 316L cylinders of diameter 11 mm and height 300 mm were realized (see Fig. 5). During the first build, no layer removal was performed, while in the second build, the process was stopped at layer 275 (13.7 mm of build height) and the removal system was activated for all the three cylinders on the build plate to remove 0.8 mm of material. Based on preliminary analyses, a continuous laser mode was chosen, with laser speed of 400 mm/s and laser power of 225 W. Layer thickness was set at 50 μm and the hatch distance at 70 μm. As regards the grinding parameters, a wheel speed of 7000 rpm and a feed speed of 20 mm/s were applied, with a depth of cut of about 20 μm, the removal procedure was repeated 40 times. After layers deletion, the powder bed was restored by iteratively recoating the powder (as described in Section 3.3) and the process started again with the same process parameters. All the six cylinders were finally machined to obtain tensile specimens in accordance with the BS EN 10002-1:2001 standard.

Specimen	Density (%)	
	without layer removal	with layer removal
1	97.32	98.64
2	94.98	98.22
3	97.31	96.87

Table 1. Specimen density measured via X-ray CT

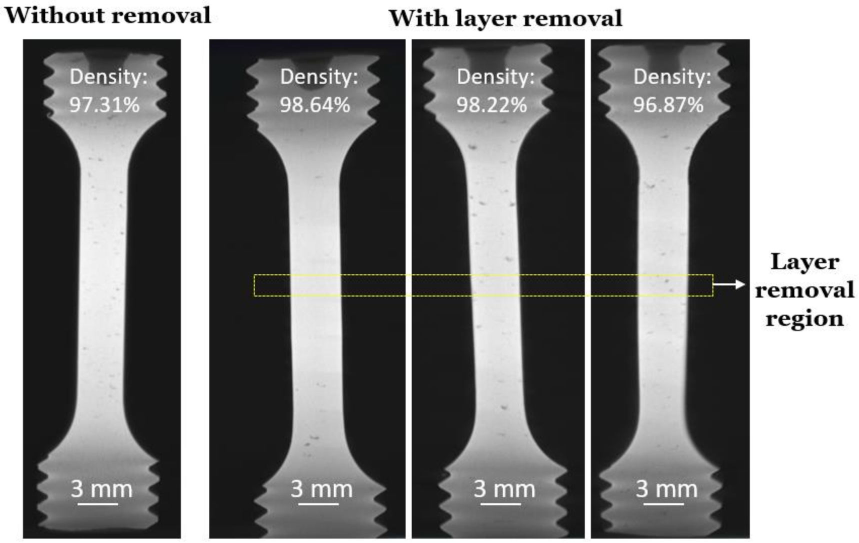

Fig. 5. Examples of X-ray CT inspections of specimens with and without layer removal

To evaluate the presence of discontinuities in the material, all the specimens were inspected via X-ray tomography with a spatial resolution of 13.8 µm/voxel. Examples of resulting cross-sections parallel to build direction in Fig 5 and in Table 1 show that internal porosity is present in the specimens with and without the layer removal and no statistical evidence of different porosity occurs between the two builds. No anomalous concentration of pores or layer delamination were detected in correspondence of the region where the grinding process was performed.

Regarding the effects of the grinding process on the powder bed surface, Fig. 6 shows in-situ images of the powder bed in different stages of the process. More in details, the left-hand side of Fig. 6 shows the in-situ image of the powder bed before the activation of layer removal procedure (just after the laser scan of the slice). The central panel of Fig. 6 shows the in-situ image of the powder bed at the end of the layer removal operation and powder bed restoration. The righ-end side of Fig. 6 shows the powder bed after the first recoating before re-starting the LPBF process. Fig. 6 shows that a contamination-free and homogeneous powder bed can be obtained before going on with the LPBF process after in-line layer removal.

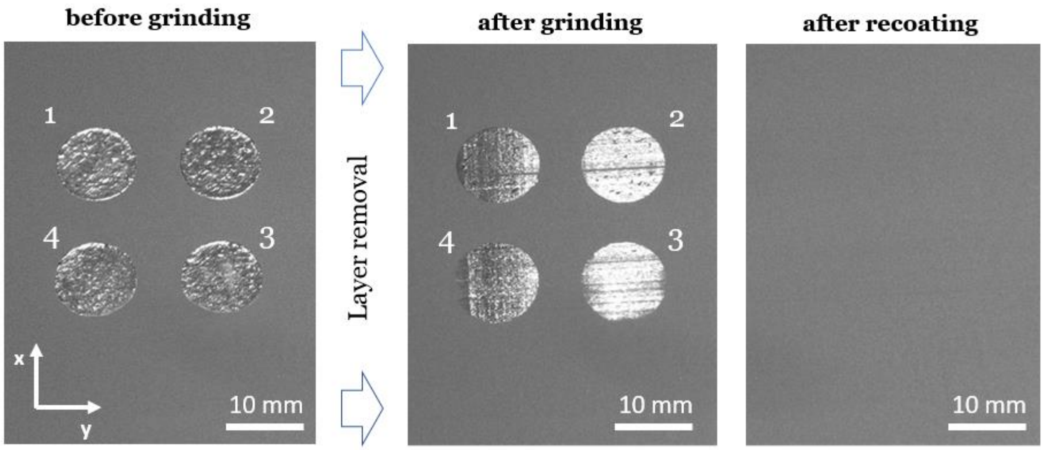

Fig. 6. Top and lateral cross-section view of the powder bed in three stages of the layer removal process.

Most of the chips produced by the grinding process are buried underneath the powder bed, mitigating the contamination of the top surface. A schematic illustration of this is shown in Fig. 7.

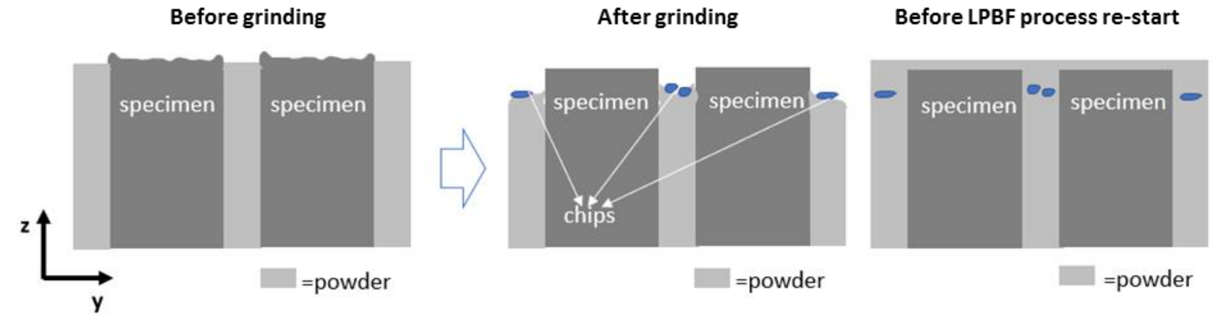

Fig. 7. Top and lateral cross-section view of the powder bed in three stages of the layer removal process.

Tensile strength tests were realized and the performances of specimens with and without layer removal were compared. Fig. 8 shows that the fracture section never occurred in correspondence of the level where the layer removal was performed, confirming the absence of localized macro-discontinuities or lack of layer adhesion. The mechanical performances, summarized in Table 2, show that UTS and yield strength of specimens with layer removal are significantly larger than those of specimens without removal, whereas two specimens out of three produced with in-line layer removal yielded a lower elongation than the others. The causes of such build-to-build variability still deserves additional analysis. Additional experiments are planned to confirm these results, and in particular to determine whether such variation is part of the natural build-to-build variability imposed by the prototype system, a consequence of the varied environmental conditions in the chamber following the process pausing (e.g., higher oxidation) or an effect of the grinding operation.

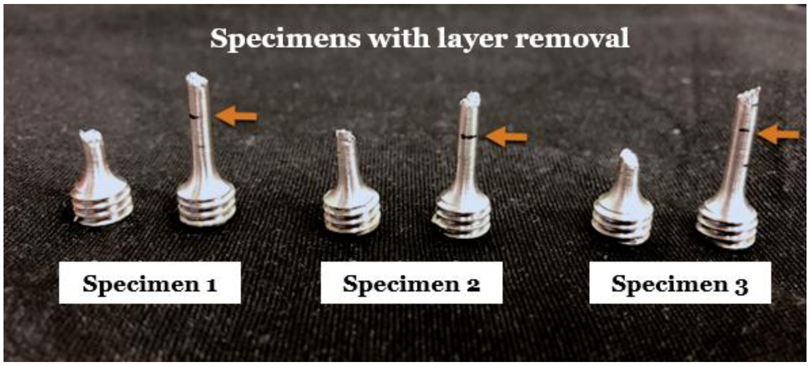

Fig. 8. Specimens of build with layer removal after tensile strength test.

	Build 1 without layer removal			Build 2 with layer removal		
Specimen ID	1	2	3	1	2	3
UTS (MPa)	489	501	501	569	562	562
YS (MPa)	467	478	472	549	528	540
E (MPa)	148436	144193	158301	205652	201718	188122
Elongation (%)	7.5	8.7	8.7	6.2	8.7	5

Table 2. Mechanical performances

Conclusions

In-situ sensing and monitoring in Additive Manufacturing are more and more regarded as enabling technologies to meet stringent qualification requirements imposed by highly regulated sectors, like aerospace and healthcare, and to enhance qualification procedures. However, there is still a lack of methods to automatically identify a defect and get rid of it during the process itself. This paper presents a novel self-repairing LPBF system, called Penelope, which combines a multi-sensor in-situ monitoring architecture with a new in-situ defect removal system. A surface grinding wheel mounted on a linear axis is integrated in the L-PBF machine. It can be activated once in-plane and out-of-plane defects are spotted by means of the vision-based monitoring system.

This study presented first preliminary results on the feasibility of the in-line defect detection and removal operation. Tensile specimens were produced with and without in-line layer removal to study the potential introduction of material discontinuities and the changes in mechanical properties. We observed that no additional porosity or localized flaws were generated as a consequence of the layer removal operation. Moreover, the first mechanical tests show that the fracture section does not occur in correspondence of the layer removal and that the average elongation increases. Further analyses are required to better understand additional effects and to confirm these preliminary findings. Finally, additional analyses on part microstructure and residual stresses will be carried out to deeply understand the effect of process interruption and grinding operations on the final part quality.

References

[1] Grasso M, Colosimo BM, *Meas. Sci. Technol.* 28(4), 044005 (2017)

[2] Everton SK, Hirsch M, Stravroulakis P, Leach RK, Clare AT, *Mater. Des.* 95, 431 (2016)

[3] Zhang B, Ziegert J, Farahi F, Davies A, *Addit. Manuf.* 12, 100 (2016)

[4] Caltanissetta F, Grasso ML, Petro S, Colosimo BM, *Addit. Manuf.* 24, 183 (2018)

[5] Craeghs T, Bechmann F, Berumen S, Kruth J, *Phys. Procedia* 5(B), 505 (2010)

[6] Mireles J, Ridwan S, Morton PA, Hinojos A, Wicker RB, *Surf. Topogr.: Metrol. Prop.,* 3(3), 034002 (2015)

[7] Yasa E, Kruth JP, Deckers J, *CIRP Ann.,* 60(1), 263 (2011)

[8] Grum J, Slabe JM, *Appl. Surf. Sci.* 252(13), 4486 (2006)

[9] Heeling T, Wegener K, *Addit. Manuf.,* 22, 334 (2018)

[10] Renken V, Von Freyberg A, Schünemann K, Pastors F, Fischer A, *Progress in Additive Manufacturing,* 4, 1 (2019)

[11] Repossini G, Laguzza V, Grasso ML, Colosimo BM *Addit. Manuf,* 16, 35 (2018)

[12] Grasso ML, Demir AG, Previtali B, Colosimo BM, *Robot Cim-Int Manuf.,* 49, 229 (2018)

[13] Grasso ML, Laguzza VL, Semeraro QL, Colosimo BM, *J. Eng. Ind.,* 139(5), 051001-1 (2017)