

Observing molten pool surface oscillations during keyhole processing in laser powder bed fusion as a novel method to estimate the penetration depth

Leonardo Caprio*, Ali Gökhan Demir, Barbara Previtali

Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy



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ABSTRACT

Various in-situ monitoring techniques have been developed for the detection of process drifts in the Laser Powder Bed Fusion (LPBF) process. Currently, optical emission monitoring can retrieve information regarding molten pool characteristics, such as temperature, width, length and area which provide substantial process signatures. Nonetheless, a fundamental indicator for the retrieval of a complete set of spatially distributed information is missing: the molten pool depth. Within the present investigation, a system for the estimation of the penetration depth based on the detection of molten pool surface oscillations is reported. Initially, the fundamentals of the monitoring technique are presented. The principle relies upon the observation of molten pool surface ripples through the measurement of probe light reflections in the melt area. Proof of concept testing of the sensing principle was conducted through an experimental investigation on a prototypal platform. A monitoring system (consisting of a high-speed camera and a secondary illumination light) was employed to view the process while realising both bead-on-plate material remelting and single track powder bed fusion depositions of AISI316L at different levels of laser emission power. Oscillation frequencies were extracted from the high-speed imaging acquisitions after image processing and signal analysis. The surface wave oscillations were measured to be in the range of 3.5–5.5 kHz in keyhole conditions. Metallographic cross-sections allowed to observe the effective molten pool penetration depth and cross-sectional area and were correlated to oscillation frequencies. Higher values of oscillation indicated shallower penetration and consequently a smaller mass of molten material.

1. Introduction

The layer-wise building principle of the Laser Powder Bed Fusion (LPBF) process enables both part qualification and defect correction through the implementation of sensing solutions. This feature has great appeal for the manufacturing sector since it lays the foundations for the digitalisation of the production chain and eventually strive for work-piece qualification [1]. The scientific community has shown how different in-situ monitoring techniques may be implemented in order to extract quality indicators which enable the identification of process drifts during the LPBF process [1–3]. Different sensors may be adopted according to the purpose of the monitoring solution being developed, the design of which is highly dependent on the nature of the phenomenon under observation, its spatial extent and dynamics [4]. For instance, pyrometers may be employed to retrieve molten pool temperature at acquisition rates greater than 50 kHz although they cannot provide spatially distributed information [5–7]. On the other hand, high speed cameras may be employed either in coaxial or lateral configuration to record spatially distributed process emission at different

wavelengths [8–11]. Other solutions which are intended for phenomenological observation of the molten metal, expose the real geometry of the molten pool by employing a secondary illumination light which dominates the process emission [12–14]. Although geometrical parameters are commonly employed as process stability indicators, a complete three-dimensional detection is limited by surface observations of the laser-material interaction. Indeed, some of the most critical defects such as porosity formation due to keyhole generation or lack of fusion are directly correlated to the melt pool depth. Hence, the quantification through direct or indirect measurement methods of indicators such as molten pool penetration depth or cross-sectional area is amongst the open challenges for the scientific community.

In literature, various monitoring methods of the LPBF process exploit surface geometrical indicators as process drift detectors. The research group from KU Leuven established control strategies based on the geometrical properties (namely width, length and area) of the molten pool and correlating them to data sampled from a photodiode [10,15]. Hooper measured molten pool surface temperature and shape through a coaxial monitoring system with two high speed cameras

* Corresponding author.

E-mail addresses: leonardo.caprio@polimi.it (L. Caprio), aligokhan.demir@polimi.it (A.G. Demir), barbara.previtali@polimi.it (B. Previtali).

List of symbols	
A_{cs}	Molten pool cross-sectional area (μm^2)
d_o	Laser beam waist diameter (μm)
f_{acq}	Acquisition frequency (Hz)
f_{osc}	Measured oscillation frequency (Hz)
$f_{phenomenon}$	Frequency of a physical phenomenon (Hz)
h	Molten pool penetration depth (μm)
I_i	Intensity of the i-th pixel bit
I_{sum}	Sum of pixel intensity values bit
l_{FOV}	Field of view length (mm)
l_{mp}	Molten pool length (mm)
M^2	Beam quality factor non-dimensional
n	Replicates non-dimensional
N_{mp}	Number of pixels of the molten pool non-dimensional
$n_{pix,x}$	Number of pixels in x-direction non-dimensional
$n_{pix,y}$	Number of pixel in y-direction non-dimensional
P	Laser emission power (W)
SR	Spatial resolution ($\mu\text{m}/\text{pixel}$)
T_{acq}	Acquisition times
TBW	Time-to-bandwidth parameter non-dimensional
v	Laser scan speed (mm/s)
w_{FOV}	Field of view width (mm)
w_{mp}	Molten pool width (μm)
α	View angle deg
β	Illumination angle deg
λ	Laser emission wavelength (nm)
$\Delta f_{min,peaks}$	Minimum distance between successive oscillation peaks (Hz)
$\Delta f_{res,MT}$	Frequency resolution for multi-taper PSD estimate (Hz)
$\Delta f_{res,PD}$	Frequency resolution for periodogram estimate (Hz)

observing the process at two specific wavelengths [8]. This technique allowed the estimation of temperature gradients, cooling rates and molten pool geometry during the scanning of overhanging geometries. Thombansen and Abels devised an in-situ monitoring system to determine geometrical parameters of the molten pool and correlate them to pyrometer measurements [6]. Demir et al. used the molten pool area to predict overheating regions during a LPBF build and employed different laser emission modes to reduce the insurgence of such defects [16]. Moreover, useful metrics related to the molten pool geometry have been extracted through off-axis high speed thermal imaging by Criales et al. [17].

Industrial systems are moving towards the adoption of in-situ monitoring strategies although the implemented approaches are often non-disclosed and mostly consist of integrated sensors such as photodiodes. Renishaw employs two photodiodes in the NIR wavelength range (one from 700–1040 nm and the other 1090–1700 nm) to track the process emission data [18]. The information may be reviewed during and at the end of the build in order to identify defective components being realised. Analogously, SLM Solutions employs a coaxial monitoring system (namely Melt Pool Monitoring) with two photodiodes to record the process emission [19,20]. EOS also developed a melt pool monitoring tool based upon the use of both a coaxial and an off-axis photodiode [21]. Trumpf also provides a molten pool monitoring system although does not declare the type of sensor employed [22]. Most recently, a novel machine manufacturer, Velo3D, has introduced a closed-loop melt pool control system which allows for the deposition of almost support-less components even for elevated overhang angle inclinations [23]. Concept Laser, on the other hand, co-developed with KU Leuven a spatially resolved in-situ monitoring system, according to the architecture previously presented [24].

The in-situ measurement of the melt pool depth has attracted attention in the last few years. Several authors have observed melt pool dynamics in LPBF by means of high speed X-ray imaging [25–31]. The technique was originally developed by Katayama et al. and Matsunawa to study keyhole dynamics during the laser welding process and further developed by researchers of the Institut für Strahlwerkzeuge, Stuttgart [32–37]. Although for phenomenological studies these works have provided extensive data, their wider industrial use as inline monitoring tools is unlikely. The use of transmitted electromagnetic waves through the large powder bed in an industrial system still requires fundamental scaling up and safety issues to be considered. An indirect approach for detecting the melt pool depth can be developed by analysing the light emitted from the melt pool [38–43]. Alternatively, surface wave oscillation detection by means of probe light reflections can be employed as an indirect penetration depth measurement method and has been conducted in both Gas Tungsten Arc welding processes and laser based processes [44–49]. Molten pool fluctuations have also been studied by

means of acoustic emission although this approach suffers from noise in industrial environments due to the low pressure of the generated sound waves [50–52]. The correlation between surface ripples and under-surface molten pool geometry was extensively studied in literature for the GTA welding technology through arc voltage monitoring [53–63]. On the other hand, a correlation between molten pool surface oscillations and penetration depth has not yet been investigated for the Laser Powder Bed Fusion technology.

Overall, the greater part of monitoring systems implemented in the LPBF process relies on the detection of electromagnetic emission of the molten pool. Although, useful indicators such as width, length, area and temperature are available as signatures for process stability, the molten pool depth is a parameter which cannot be directly detected with in-situ process monitoring tools adaptable to industrial systems. The aim of the present investigation is thus to present a monitoring approach for the indirect measurement of the penetration depth. The principle upon which the monitoring system is developed is based on the detection of surface oscillations via reflections of a secondary illumination light. The current work firstly presents the penetration depth estimation approach adopted and defines the design criteria for the monitoring solution that will be developed. Successively the experimental setup employed to validate the monitoring technique is detailed in the materials and methods section. Within the same section, the image and signal processing methodologies are presented, as well as the experimental campaign. Results report the molten pool oscillation frequency in different experimental conditions and the metallographic cross-sections of the samples. Finally, the surface oscillations are correlated to the under-surface geometrical parameters of the molten pool (penetration depth and cross-sectional area) alongside with a discussion of the results.

2. Penetration depth estimation approach

In the subsequent section, the novel penetration depth estimation approach is presented alongside with the design criteria for the realisation of the in-situ monitoring technique.

2.1. Physical principle

Based upon the various monitoring approaches presented in the literature review, a novel sensing principle for the estimation of the molten pool penetration depth in the LPBF process was investigated. Different researches conducted on the GTA welding technology highlighted the link between molten pool surface oscillations and its geometrical parameters [38,55,57,60]. It is commonly accepted that the molten pool dynamics for laser based processes are dominated by three contributions: thermo-capillary forces, recoil pressure and surface tension (also referred to as capillary forces) [28,64]. The thermo-capillary

forces are generated by the elevated temperature gradients present in the melt pool which cause Marangoni convection [28,65]. The recoil pressure generated by localised evaporation of the base material due to the high intensity laser beam which causes plasma formation and eventually keyhole formation [66,67]. Recoil force and thermo-capillary convection are countered by surface tension components of the molten liquid (i.e. capillary forces). The combined action of these components on the liquid metal are shown to induce oscillatory motion which may thus be compared to that of GTA welding [28,53].

Variations in the processing parameters will affect both the forces and thermal phenomena acting on the molten pool as well as the boundary conditions thus inducing variations in the surface oscillations. The role of such forces on the molten pool surface deformations and track geometry has been confirmed by computational thermo-fluid dynamic simulations conducted by Khairallah and Anderson [68]. With elevated energy intensities, recoil pressure forces play a major role in dominating the fluid flow whilst surface tension forces become predominant at lower energy levels, eventually inducing Plateau-Rayleigh instabilities in the molten metal [68,69]. If it is possible to correlate the surface oscillations to the geometrical parameters of the molten pool then the challenge regards the development of a technique suitable for the online measurement of the waves and the data processing associated to this technique. As previously shown by Semak et al., the use of a probing light is an optimal solution for the detection of waves on the molten pool surface [46]. Accordingly, previous high speed imaging observations by the authors using a secondary illumination source showed that bright reflections could be identified on the molten pool area [70]. Similarly, Kovacevic and Zhang [71,72] employed a secondary laser light to depict deformations of the molten pool surface. Surface oscillation monitoring tools have been principally applied to laser and torch welding but may be considered valid for LPBF due to the analogies in terms of heat source and base material. In literature, an approach often employed is to study both the LPBF and material remelting processes. For instance, Cunningham et al. compared single track depositions with bead-on-plate material remelting and reported differences in the molten pool penetration depth in the remelting conditions with respect to LPBF, whilst in the latter the keyhole appeared to possess a more turbulent behaviour [73]. Nonetheless, a specific analysis of the surface oscillations to quantitatively determine differences (if present) was not conducted. Moreover, Gunenthiram et al. identified surface ripples during LPBF which allows to consider light probing methods as applicable for surface oscillation detection [74].

A representative frame of a high speed imaging acquisition is shown in Fig. 1(a), whilst Fig. 1(b) reports its schematic representation. The

deposited material is clearly visible due to the denudation area of the powder bed and its clear contours. The molten pool is evidenced by its dark appearance and due to its dynamic nature. The laser material interaction area appears in light grey colour. On the other hand, it is possible to clearly distinguish bright reflections of the illumination light which appear in white due to their high intensity.

Accordingly, the bright reflections can be assumed to be representative of the oscillatory peaks of the liquid metal as shown schematically in Fig. 2. The incoming illumination light is locally reflected at a given incident angle and can thus be captured by a camera or integrated sensor.

2.2. Design criteria for the melt pool surface oscillations monitoring system

As previously indicated, the measurement of the molten pool surface observations may be conducted with a high speed imaging setup. This monitoring system is required for the proof of concept demonstration of the sensing approach due to its capability to view the molten pool with sufficiently elevated temporal and spatial resolutions (requirements dictated by the oscillatory phenomenon). High speed imaging setups are generally used in off axis configuration and will be consequently implemented in the present work for the proof of concept of the novel penetration depth estimation approach. For a correct estimation of the molten pool oscillations it is important to define the design cues of the high speed imaging setup.

In order to determine the molten pool oscillations through spectral analysis it is required to maintain both the frequency resolution and the acquisition frequency as high as possible. This respectively allows to minimise errors related to the redistribution of the signal energy and aliasing. On the other hand, it is mandatory to maintain a high spatial resolution in order to detect the molten pool features [4]. To maximise the acquisition frequency of a high speed camera the number of active pixels of the sensor must be minimised due to data transfer rate limits. The geometry of the single track deposition can aid in reducing the number of active pixels (for instance by restricting the width and length according to the geometry that is going to be observed). The most important aspect is that the acquisition frequency (f_{acq}) of the high speed imaging camera should be at least twice the frequency of the phenomenon ($f_{phenomenon}$) in order to avoid aliasing of the phenomenon:

$$f_{acq} \geq 2f_{phenomenon} \quad (1)$$

The leakage effect may also cause errors in the identification of the oscillation frequency especially when neighbouring peaks are within the narrow bandwidth of the Power Spectral Density (PSD) estimate. Therefore, the frequency resolution Δf_{res} must be selected below an a

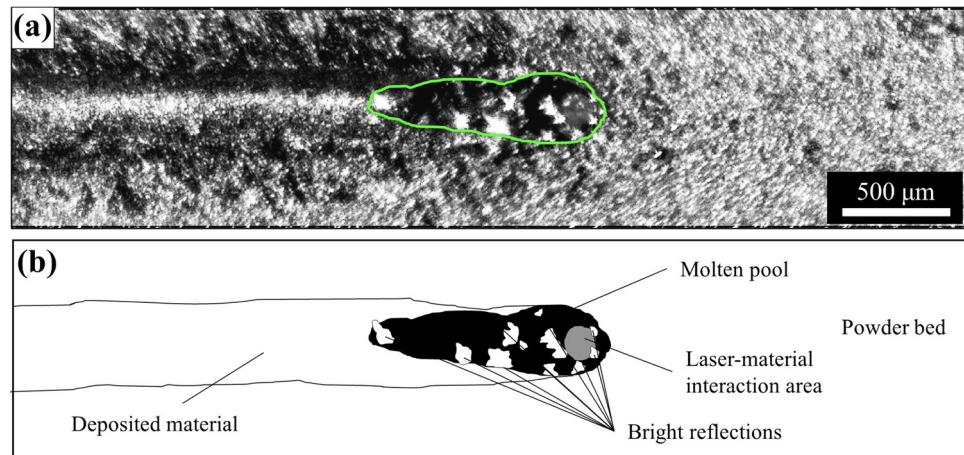


Fig. 1. (a) Frame from high speed imaging acquisition of a single track LPBF deposition (molten pool outline shown in green), (b) schematic representation indicating different elements.

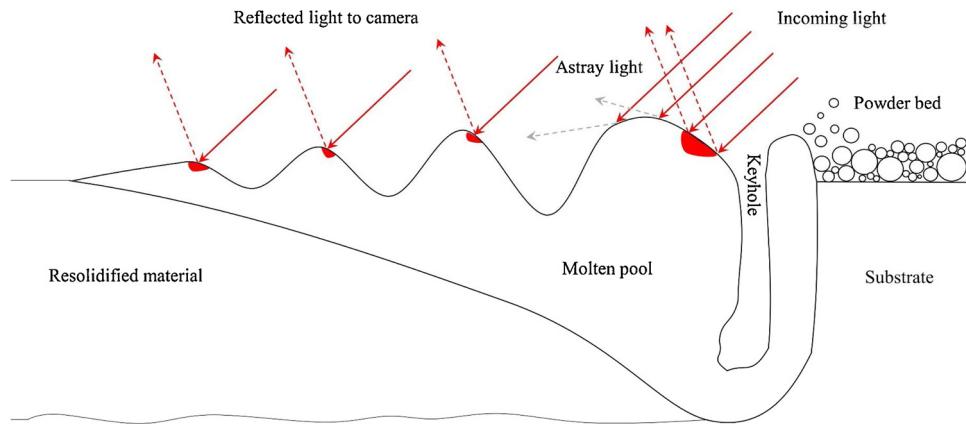


Fig. 2. Schematic representation of a transversal view of the molten pool during the LPBF process.

a priori estimated value of the minimum distance between two successive oscillation peaks $\Delta f_{min,peaks}$ (in the case where more than one pole is expected in the transfer function of the oscillating system). Hence, the following equation defines this constraint:

$$\Delta f_{res} \leq \Delta f_{min,peaks} \quad (2)$$

Another aspect to take into account is that an off-axial setup, often employed for high speed imaging, observes the process from a fixed point of view (contrarily to coaxial monitoring setups which view the process from a Lagrangian perspective) and hence introduces a limitation in terms of the acquisition time (T_{acq}). This generates a constraint in the frequency resolution of the periodogram estimate ($\Delta f_{res,PD}$) of the Power Spectral Density, according to the following relationship [75]:

$$\Delta f_{res,PD} = \frac{1}{T_{acq}} \quad (3)$$

The frequency resolution of the PSD estimate is also affected by the window functions employed to reduce the leakage error. This aspect will be further discussed in section 3.3.3 *Signal processing*. For a preliminary evaluation of the performance of the oscillation frequency detection system, the frequency resolution of the periodogram estimate may be employed for a base line evaluation. The acquisition time may be determined as a function of the process parameters and the field of view of the off-axis configuration. The schematic representation of the first and final frames of the acquired video for a single track LPBF deposition is shown in Fig. 3. The first useful frame may be considered when the molten pool is fully contained within the field of view whilst the final frame corresponds to when the front of the molten pool reaches the end of the field of view.

Hence, the distance travelled by the molten pool may be considered as the difference between the length of the field of view l_{FOV} and the length of the molten pool l_{mp} . The latter is changing instant by instant and will be affected by process parameters such as laser emission power (P) and scan speed (v) but an expected maximum value may be determined. The acquisition time may therefore be formulated as:

$$T_{acq} = \frac{l_{FOV} - l_{mp}}{v} \quad (4)$$

It is thus possible to define the periodogram resolution in the frequency domain as:

$$\Delta f_{res,PD} = \frac{v}{l_{FOV} - l_{mp}} \quad (5)$$

The field of view length can also be expressed in terms of the active pixels in the horizontal direction $n_{pix,x}$ and of the spatial resolution of the imaging setup SR with the following equation:

$$l_{FOV} = n_{pix,x} \cdot SR \quad (6)$$

Therefore, it is possible to express the obtainable resolution in the frequency domain as:

$$\Delta f_{res,PD} = \frac{v}{n_{pix,x} \cdot SR - l_{mp}} \quad (7)$$

With regards to the field of view dimension in the vertical direction w_{FOV} (i.e. perpendicularly to the scanning direction) the minimum size should be greater than the molten pool width w_{mp} :

$$w_{FOV} \geq w_{mp} \quad (8)$$

This relationship may be expressed in terms of the number of active pixels in the vertical direction $n_{pix,y}$ and of the spatial resolution of the imaging setup SR :

$$n_{pix,y} \cdot SR \geq w_{mp} \quad (9)$$

Taking into account all of the constraints previously mentioned and the aims of the present investigation, it is possible to summarize them in Table 1.

3. Materials and methods

3.1. Laser powder bed fusion system

A flexible prototype system for LPBF namely *Powderful*, was used throughout this work. The mechanical system consisted of a custom-

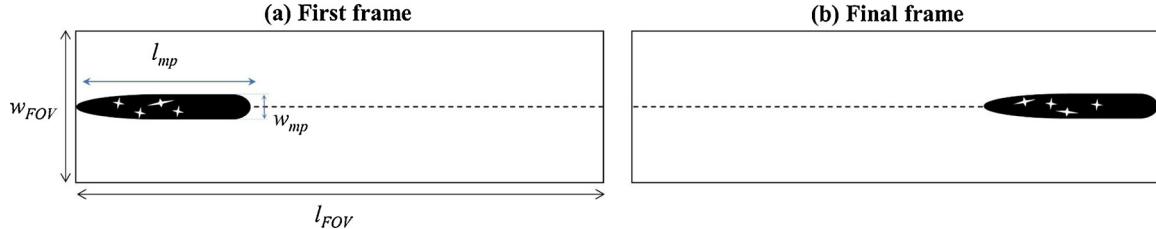


Fig. 3. Schematic representation of (a) first and (b) final frame of a video acquisition indicating molten pool geometrical characteristics and field of view parameters.

Table 1

Molten pool observation system parameters.

Parameter	Lower limit	Upper limit	Formula
Field of view width, w_{FOV}	$> w_{mp}$	–	–
Field of view length, l_{FOV}	–	Process limited	$l_{FOV} = n_{pix,x} \cdot SR$
Spatial resolution, SR	Optically limited	Resolution limited	–
Acquisition frequency, f_{acq}	$> 2 \cdot f_{phenomenon}$	Data transfer rate limited	–
Frequency resolution, Δf_{res}	As small as possible	$\Delta f_{res} \leq \Delta f_{min,peaks}$, Process limited	$\Delta f_{res} = \frac{v}{n_{pix,x} \cdot SR - l_{mp}}$

made powder bed able to process small quantities of powder (< 500 g). Detailed description of the mechanical system may be found in previous publications [70,76]. The laser source for the powder bed fusion process was a single mode fiber laser with 1000 W maximum emission power (nLIGHT alta, Vancouver, WA, USA). The laser light is emitted from the source at an emission wavelength $\lambda = 1080$ nm with a beam quality factor $M^2 = 1.19$. The diverging laser beam was collimated with a 75 mm lens, which was manipulated and focused by a scanner head (Smart Move GmbH, Garching bei München, Germany). The collimated beam was focused onto the working plane with a 420 mm F-theta lens. With the current optical setup, the beam waist diameter at the focal plane (d_0) was calculated as 78 μm . The control of the mechanical system and monitoring of the machine state were carried out in LabVIEW environment (National Instruments, Austin, TX) and the trajectories of the laser beam were designed with ScanMaster Designer software (Cambridge Technologies, Bedford, MA, USA).

3.2. Materials

In the present investigation AISI316L stainless steel was employed as substrate material (12 mm thickness) both for the bead-on-plate and LPBF experiments. For the single track Laser Powder Bed Fusion depositions, the powder was provided by Cogne Acciai (Brescia, Italy) with granulometry comprised between 15 and 45 μm . Chemical composition of the powder is reported in Table 2.

3.3. Measurement of the melt pool oscillations

3.3.1. High speed imaging equipment

The imaging setup consisted in a high speed camera with a CMOS sensor (Fastcam Mini AX200, Photron, Tokyo, Japan) and a secondary illumination laser Cavitux HF (Cavitar, Tampere, Finland) as presented in a previous work [70]. The secondary illumination light was a pulsed laser source emitting at 640 nm, where the pulsation frequency was regulated according to the acquisition rate of the high-speed camera. Exposure time of the CMOS sensor corresponded to 666 ns and was regulated to include the whole pulse duration of the illumination light (600 ns), according to monitoring design cues defined in a previous publication [4]. The complete experimental setup and monitoring system are shown in Fig. 4.

3.3.2. Image processing

The overall methodological approach developed may be summarized in the block diagram reported in Fig. 5.

The Laser Powder Bed Fusion process is observed through high speed imaging and the use of an external illumination source. The acquired frames are processed through the algorithm presented in section 6 Appendix whilst the various image processing steps are shown in Fig. 6.

The oscillation indicator is thus extracted (sum of intensity of melt pool pixels I_{sum}) for every time instant and is defined as follows:

$$I_{sum} = \sum_{i=1}^{N_{mp}} I_i \quad (10)$$

Where I_i is the intensity of the i-th pixel contained within the melt pool

area and N_{mp} the total number of pixels of the melt pool so that I_{sum} is representative of the surface reflections of the molten pool. Subsequently, the time dependent signal is used to estimate the Power Spectral Density using Thomson's multi-taper method and hence allows to extract an indicator which is representative of the molten pool oscillation frequency.

Fig. 7 shows acquired frames at different time instants ((a), (b) and (c)) and overlayed on the original frame, the corresponding melt pool determined with the molten pool identification algorithm ((d), (e) and (f)). It is possible to view the whole video and corresponding algorithm calculations in the supplementary video n.1 provided.

The melt pool identification algorithm is useful in extracting the geometrical parameters related to the molten pool in terms of average value. Nonetheless, it still presents errors which might compromise its performance in evaluating front and side oscillations. For instance, errors are induced when an ejected particle is near the molten pool since the dilation step of the image processing code causes it to be considered as part of the molten pool. Moreover, the spatial resolution of the imaging setup is another limitation in detecting clearly front and side oscillations of limited entity. Still, for the aim of the present work, whereby the oscillation indicator is composed of the global intensity sum of the molten pool, an error of reduced entity is induced by the limitations of the molten pool identification algorithm. Due to the size and intensity of spatter, when ejections are located within the identified molten pool, they may introduce a disturbance in the measurement of I_{sum} . Still, the influence of the latter on the Power Spectral Density estimate may be considered as limited since they only introduce brief time-localised disturbances.

3.3.3. Signal processing

In order to identify the oscillation frequency, once the indicator of interest was extracted through the image processing code, signal processing in the frequency domain must be conducted. Under the hypothesis that the LPBF process at single track level can be considered as a stationary process, the identification of the oscillation modes can be conducted by estimating the Power Spectral Density (PSD). Accordingly, it is possible to estimate the PSD employing either parametric or non-parametric estimates [77]. Although, parametric estimates of the Power Spectral Density tend to be better performing when short duration records are acquired, they also imply the *a priori* choice of a model order and number of poles of the transfer function [78]. Hence, for an initial investigation of the oscillation modes of the molten pool the use of non-parametric estimates may be considered as an appropriate choice.

The periodogram estimate of the PSD, may be computed by using the Discrete Fourier Transform of the original time-dependent information representative of the oscillations I_{sum} , according to the

Table 2

Chemical composition of AISI316L stainless steel powder as declared by the producer.

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Co	Ti	Fe
wt (%)	0.020	0.52	1.50	0.010	0.007	17.3	2.46	11.4	–	–	Bal.

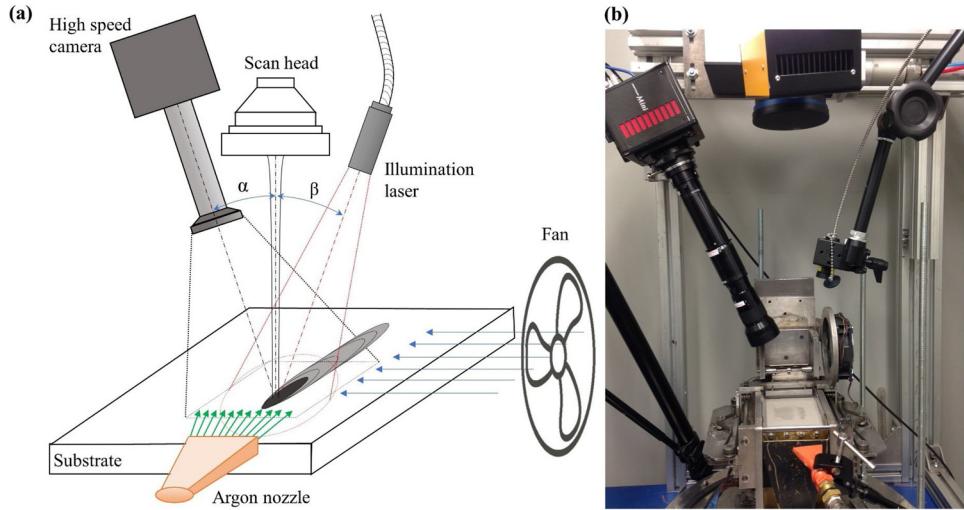


Fig. 4. Experimental setup (a) schematic representation and (b) effective realisation.

formulation reported in Carter and Nuttall [75]. However, the periodogram is a non-consistent estimate of the PSD. Therefore, by separating the original record in a set of sub-records and averaging the respective periodogram estimates allows to obtain a consistent estimate of the PSD (Bartlett's method) [75]. The cost of this operation is in terms of the frequency resolution (which thus depends on the length of the sub-record). A better performing solution is Welch's method whereby an overlapping travelling window is employed for the division of the record prior to the averaging step [75]. Nonetheless, also this approach penalises the frequency resolution of the estimate. Alternatively, Thomson's multi-taper method (whereby the signal is filtered through a set of orthogonally independent windows and averaging the result) may be employed to reduce the loss in frequency resolution whilst minimising the error of the estimate [79]. It has been shown that this method has advantages over single-taper estimates of the PSD [80]. In the case of Thomson's multi-taper method, the time-to-bandwidth parameter regulates the temporal and frequency resolution of the estimate and is defined as [81]:

$$TBW = \frac{T_{acq} \cdot \Delta f_{res,MT}}{2} \quad (11)$$

where T_{acq} corresponds to the acquisition time and $\Delta f_{res,MT}$ to the frequency resolution obtainable with Thomson's multi-taper method. However, as the TBW parameter is increased, the confidence interval of the estimate is reduced at the expense of a loss in the frequency resolution which can cause smoothing of the spectral estimate and loss of information. On the other hand, a too low TBW parameter can generate poor estimates of the PSD due to the excessively large confidence interval. In accordance with the design cues detailed in section 2.2, the time-to-bandwidth parameter must be selected appropriately.

Fig. 8 reports the result of the PSD estimates obtained with different methods. The periodogram estimate presents excessive noise and can

induce errors in the oscillation frequency identification. Both Thomson's multi-taper method and Welch's method allow for a correct estimate of the main oscillation frequency but Welch's method tends to smooth excessively neighbouring secondary peaks (view detail in Fig. 8(b) where P2 is not present in the estimate computed with Welch's method). Thomson's multi-taper method allows for a better identification of the different features of the PSD.

3.3.4. Implementation

The choices regarding the monitoring system parameters, based upon the design cues indicated previously in section 2.2, were made taking reference from the literature and verified by means of preliminary experiments to ensure that the molten pool geometry was contained within the field of view of the imaging equipment. In terms of molten pool length, for AISI316L Bruna Rosso et al. reported a maximum value of $l_{mp} = 1.4$ mm, Scipioni Bertoli et al. values in excess of 1.5 mm whilst Heigel and Lane measured values slightly below 1 mm for the LPBF of IN625 [9,13,82]. For the estimation of the obtainable frequency resolution, we will be employing a reference value of $l_{mp} = 1.5$ mm as previously done for the design of a coaxial monitoring system for LPBF [4]. With regards to the molten pool width, Brunarosso et al. measured values in excess of 250 μm while Cheng et al. values in the order of 400 μm [82,83]. This parameter may be also determined after the single track deposition process. Yadroitsev et al. measured values of 140 μm for the single track deposition of AISI316L and 130 μm for AISI904L [84,85]. The authors of the current work, with parameters similar to those planned for the current experimental campaign ($P = 250$ W, $v = 50$ mm/s), measured track width values in the order of 400–500 μm for the single track deposition of AISI316L [70]. Hence, a field of view width greater than 500 μm is required.

Spatial resolution SR should be at least one order of magnitude smaller than the minimum characteristic feature of the process under

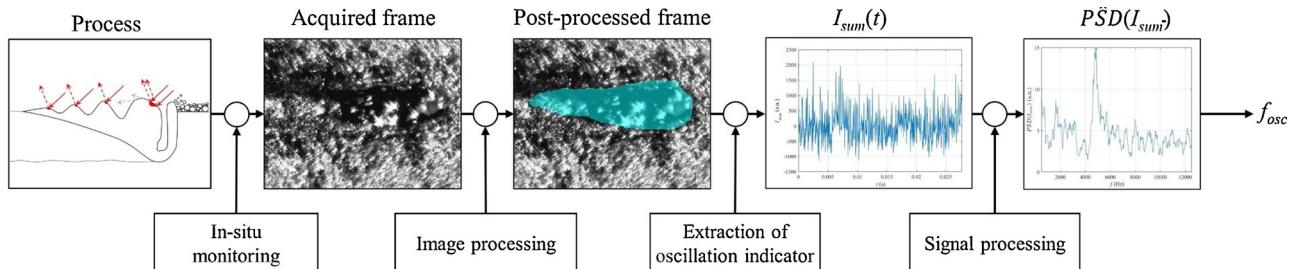


Fig. 5. Block diagram of the methodological approach developed.

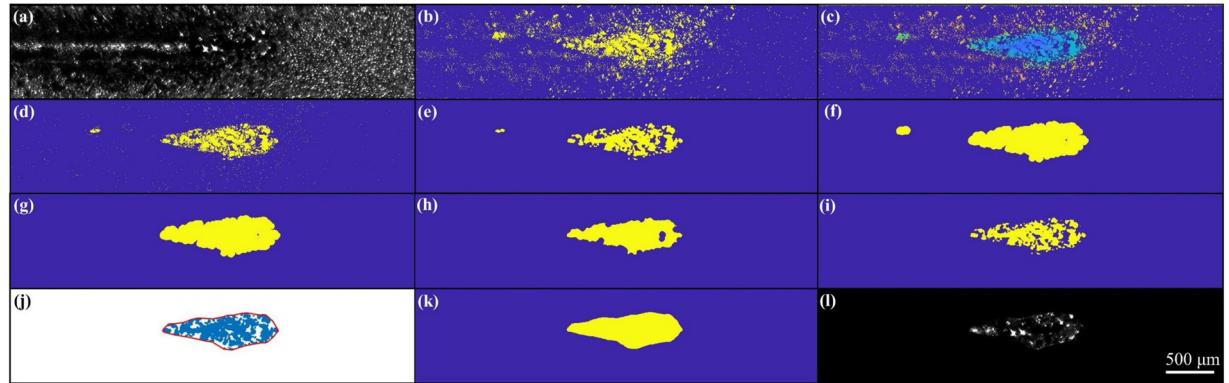


Fig. 6. Different steps of the image processing algorithm developed: (a) raw image (b) background removal (c) frame after frequency filtering with Butterworth high pass filter (d) frame after hard thresholding (e) after median filtering (f) after dilation (g) area threshold removal (h) image erosion (i) median filtered image \times eroded image (j) boundary reconstruction (k) molten pool shape (l) extracted molten pool.

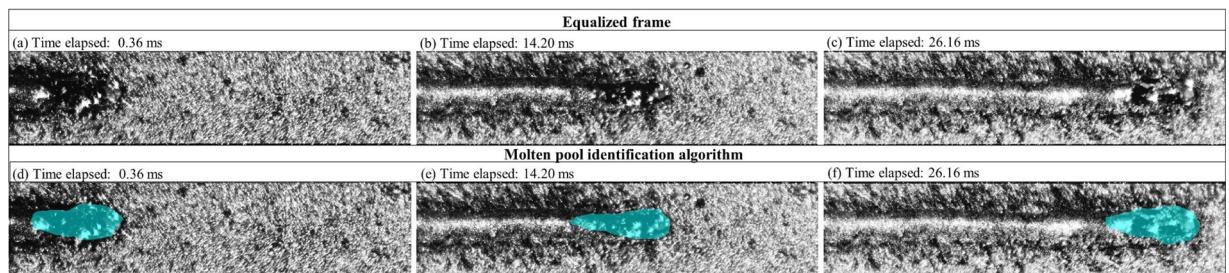


Fig. 7. Supplementary video n.1 showing acquired frame and molten pool identification algorithm result respectively (a) and (d) at an initial phase, (b) and (e) in a central position and (c) and (f) towards the end of the acquisition. Process parameters are $P = 300$ W, $v_{\text{scan}} = 100$ mm/s.

observation [4]. For the present investigation, a value of $SR = 4 \mu\text{m}/\text{pixel}$ was chosen in order to verify this condition and enhance the performance of the image processing algorithm. Having defined the imaging requirements of the phenomenon under observation, the choice of the field of view becomes a compromise between the acquisition frequency and the obtainable frequency resolution constrained by the available data rate of the high-speed camera.

GTA welding oscillation values are typically in the order of some hundred hertz as shown by Xiao and Den Ouden [59,60], Andersen [38] and Renwick and Richardson [53]. However, literature from the laser welding has reported oscillations both in the order of hundreds and kHz levels: 2–3 kHz according to Matsunawa et al. for A5083 [32], 500 Hz to 2.5 kHz for Semak et al., 100–600 Hz for Geiger et al. for steel [43], 10 kHz according to Kouraytem et al. for AISI304 [28]. Specifically, oscillations for the Laser Powder Bed Fusion process have been reported by Richter et al. to be comprised between 4 and 8 kHz for a CoCr alloy [29]. With the high-speed camera in use for the present

experimentation, selecting a number of pixels which ensures that the molten pool width is contained within the field of view and maximising the number of pixels in the x-direction (i.e. longest FOV possible) to obtain the highest frequency resolution, the acquisition frequency will correspond to 25 kHz. This condition will avoid the aliasing phenomenon according to oscillation values reported in literature whilst allowing for enough resolution to identify the oscillation frequency. Moreover, the baseline frequency resolution (i.e. periodogram estimate of the PSD) of the oscillation detection method will correspond to $\Delta f_{\text{res},PD} = 38.5$ Hz. In order to decrease the leakage effect and provide a consistent estimate of the Power Spectral Density (as discussed in the previous section) to enable oscillation frequency identification, Thomson's multitaper method was employed with a time-to-bandwidth parameter $TBW = 6.5$. Since, T_{acq} is constrained by the field of view and spatial resolution, according to Eq. 11 this will yield a frequency resolution of $\Delta f_{\text{res},MT} = 501$ Hz. Although, this parameter appears to introduce a significant bias in spectral estimation, it must be recalled that

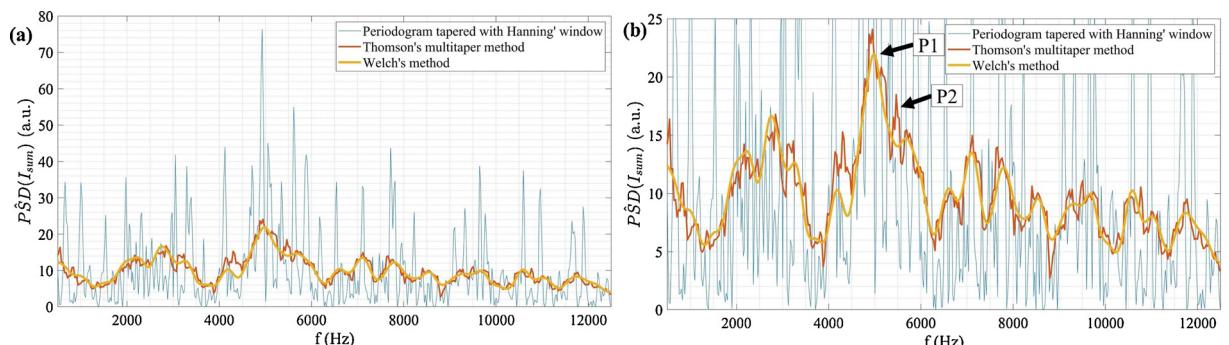


Fig. 8. Alternative methods to remove noise from power spectral density estimate. (a) Periodogram tapered with Hanning's window in blue, Welch's method estimate in orange and Thomson's multi-taper method in yellow estimate. In (b) a magnified view of (a) with indication of principal oscillation peak P1 and secondary oscillation peak P2.

it mostly indicates the capability of the spectral estimate to distinguish neighbouring oscillation peaks. Literature shows that often single oscillation peaks related to specific oscillation modes are detected (according to Xiao and Den Ouden [59]) and in the case of laser based processing, if more than one mode is determined, the oscillation frequencies are distanced by several hundreds of hertz, even kHz [41]. The overall choice of parameters for the molten pool oscillation monitoring system for the present investigation are reported in [Table 3](#).

3.4. Experimental plan

To investigate if the novel monitoring system devised can effectively detect variations in penetration depth and molten pool geometry, an experimental campaign for both bead-on-plate material remelting and LPBF single track processes was conducted. Both processes were considered for this initial investigation since baseline evaluation of the monitoring method may be conducted on the material remelting experiments and successively extended to the Laser Powder Bed Fusion technology. The laser scan tracks were 20 mm long and the process was observed in the central part of the single tracks (for a length corresponding to the horizontal field of view dimension). In order to induce variations in the molten pool geometry the experiments were conducted at three levels of laser emission power (ranging from 200 to 300 W). The substrate material was AISI316L for both processes whilst powder with a layer thickness of 50 µm was spread via the mechanical layering system for the LPBF tests. Focal position was kept fixed on the working plane and scan speed of the beam was maintained at 100 mm/s. Local shielding of the melt area was achieved by means of a nozzle which delivered Argon gas. The processing conditions employed were shown to produce thin wall geometries in preliminary experiments conducted by the authors and are similar to those employed during previous single track investigations [86]. Moreover, a fan was employed to protect the laser systems from spatter ejections. Every experimental condition was replicated two times. Details of the fixed and variable factors of the experimental campaign are reported in [Table 4](#).

For each single track, high-speed video images were acquired while four cross-sections were prepared for metallographic analysis and measurement of the resolidified material. The surface of the specimens was prepared through polishing and chemical etching. The chemical composition of the acid solution was 1 mL of nitric acid 65 % concentration, 1 mL of chloridic acid 37 % concentration and 1 mL of water. The AISI316L single tracks were exposed 1 min in the acid solution.

The chemical etching procedure disclosed the geometry of the molten pool that was successively acquired through optical microscopy (Ergolux 200, Leitz, Stuttgart, Germany). Different geometrical indicators could be retrieved through the metallographic cross-sections but for the aim of the present work results related to molten pool cross-sectional area (A_{cs}), and penetration depth (h) will be presented. A representative cross-section of a single track LPBF deposition is shown in [Fig. 9](#), indicating the geometrical features measured.

4. Results

4.1. Oscillation frequencies

Supplementary video n.2, reports the high-speed imaging acquisition of one replicate for every experimental condition (a representative frame is shown in [Fig. 10](#)). It is clearly possible to view how molten pool area, width and length all increase with higher levels of emission power. Even though the bright reflections representative of the molten pool oscillations can be identified throughout all the experimental conditions observed (with a motion from laser-material interaction position towards molten pool tail), it is difficult to make qualitative observations regarding the oscillation frequencies. Spatter ejections from the laser material interaction area during the material remelting

experiments can be viewed in supplementary video n.2. Observing the video acquisitions, it was possible to denote that spatter formation occurred rarely and inconsistently above the molten pool area identified by the image processing algorithm, thus confirming the hypothesis of non-periodic disturbances in the measurement chain. On the other hand, spatter identification for the single track LPBF depositions was challenging since their presence was disguised by the motion of powder particles near the laser-material interaction position. Still, their influence is expected to be analogous to that observed in the material remelting experiments. Further insight into the spatter ejection frequency might be disclosed by observing the process without the secondary illumination light or at different wavelengths (as done by Criales et al. [17]) but was beyond the scope of the present investigation.

The analysis of the I_{sum} indicator in the spectral domain with the methodology previously introduced is useful to disclose the oscillation frequency of the molten pool. Power spectral density estimates are shown in [Fig. 11](#) for all experimental conditions tested in the current work. f_{osc} can be identified by the maximum value of the PSD estimates which indicates the frequency where the highest signal energy may be found.

In the high speed imaging acquisitions (shown in [Fig. 10](#) and in supplementary video n.2), it is possible to view that the pixels corresponding to the bright reflections are saturated whilst pixels in correspondence of the troughs of the waves correspond to a zero reading. This is a limitation correlated to the dynamic range of the imaging setup and effectively causes a hard clipping of the signal. Hence, in the PSD estimates reported in [Fig. 11](#), this effect can modify the amplitude of the oscillation peak and introduce disturbances by adding frequency components in the neighbouring bins. Still, concerns regarding the amplitude are not of interest for the aims of the present work whilst the disturbance does not hinder the identification of the oscillation peaks so the dynamic range employed may be deemed satisfactory.

The oscillation frequencies detected during the present study are in the kHz range and tend to decrease with increasing levels of emission power. The decreasing trend can be considered to be correlated both to the increasing mass of molten metal and variations in the amount of penetration depth. Both parameters affect the oscillation frequency in such sense according to the analytical models proposed by Sorensen and Eagar [57], Xiao and Den Ouden [59] and Yoo and Richardson [87]. In the majority of cases, the spectral estimates show a single oscillation peak in the range of 3.5–5.5 kHz. However, secondary oscillation peaks (of lower predominance) may be identified. This may be symptomatic of the presence of the superposition of oscillation modes. It may be argued that the choice of the time-to-bandwidth parameter may affect the presence of secondary oscillation peaks due to the reduction of the frequency resolution as it is increased. Nonetheless, a preliminary sensitivity analysis (not reported integrally for brevity) on the effect of the TBW parameter on the PSD estimate highlighted that for the current experimentation a variation of its value from 4 to 10 (corresponding to $\Delta f_{res,MT} = 300 - 800$ Hz) did not significantly affect

Table 3
Selected parameters of molten pool oscillation measurement system.

Parameter	Value
Configuration	Off-axis
View angle, α	30°
Illumination angle, β	10°
Melt pool length, l_{mp}	1.5 mm
Melt pool width, w_{mp}	500 µm
Acquisition rate, f_{acq}	25 000 Hz
Spatial resolution, SR	4 µm/pixel
Field of view, FOV	1024 pixels x 240 pixels 4.096 mm x 0.96 mm
Periodogram frequency resolution, $\Delta f_{res,PD}$	38.5 Hz
Time-to-bandwidth, TBW	6.5
Multi-taper frequency resolution, $\Delta f_{res,MT}$	501 Hz

Table 4
Fixed and variable factors of experimental campaign.

Fixed factors	
Process gas	Argon
Material	AISI316L
Scan speed, v (mm/s)	100
Beam waist diameter, d_0 (μm)	78
Replicates, n	2
Variable factors	
Process	Material remelting, LPBF
Power, P (W)	200; 250; 300

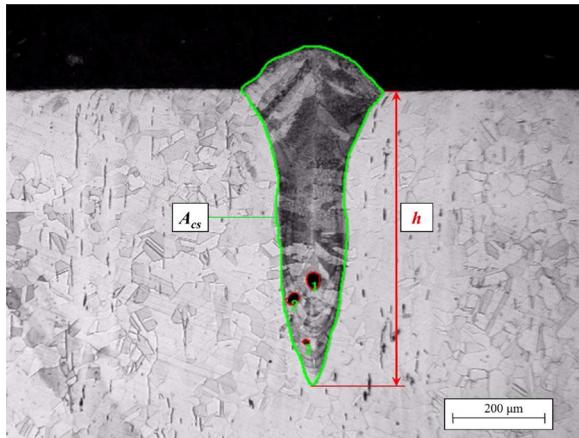


Fig. 9. Geometrical parameters measured from metallographic cross-sections.

the main oscillation frequency estimate. Accordingly, the surface wave oscillations detected during the present work may be compared with results reported in literature as shown in Fig. 12.

4.2. Single track dimensions

In Fig. 12, it is possible to view how the results obtained in the present investigation are comparable to the ones measured through high-speed X-ray transmission imaging by Richter et al. during the LPBF of a CoCr alloy [29]. On the other hand, oscillation values are well

above the frequencies reported for the GTAW process as could be expected since the size of the weld pool of arc based processes is greater even by an order of magnitude in comparison to laser based processing.

From each metallographic cross-section it was possible to measure A_{cs} (which may be taken as representative) and the penetration depth h with respect to the oscillation frequency, (representative conditions are shown in Fig. 13). Within all the combinations tested, the bead geometry indicates the presence of a keyhole and porosity caused by gas entrapment. Although, keyhole formation as a condition should be avoided in Laser Powder Bed Fusion, this result does not affect the outcome of the present experimentation whose aim is to verify the correlation between melt pool surface oscillations and under surface parameters.

As could be expected and may be viewed qualitatively in Fig. 13, tracks with higher penetration depths correspond to conditions where higher emission power was employed. In these conditions, the oscillation frequency detected by the monitoring system is lower and can be explained by the greater mass of molten material due to the higher energetic input. For this reason, also the cross-sectional area may correlate well to the oscillation frequencies detected.

Fig. 14 shows the values of the output variables of the present experimentation as a function of the laser emission power. At constant process parameters the material remelting experiments show slightly higher penetration depth with respect to the powder bed fusion depositions whereas with regards to the melt pool length no significant difference could be established. Measurements regarding the penetration depth are in accordance with the results reported by Cunningham et al. [73]. As the laser emission power increases the molten pool length concurrently increases (as previously observed by Heigel and Lane during the LPBF of IN625 [11]). As shown by the trends of Fig. 14, for both the LPBF and material remelting experiments, a decrease in oscillation frequency (Fig. 14(d)) corresponds to an increase in molten mass (represented by the cross-sectional area A_{cs} Fig. 14(b) and molten pool length Fig. 14(c)). This concurrently also corresponds to an increase of penetration depth (Fig. 14(a) and (d)) indicating a link between these parameters.

From the graphs of Fig. 14, it appears that with analogous process parameters the molten pool of the LPBF process might have higher oscillation frequencies with respect to material remelting (especially at higher levels of emission power). However, no statistical difference between the two processes could be asserted. In order to disclose better

Time elapsed: 15.92 ms – Frame 398/694

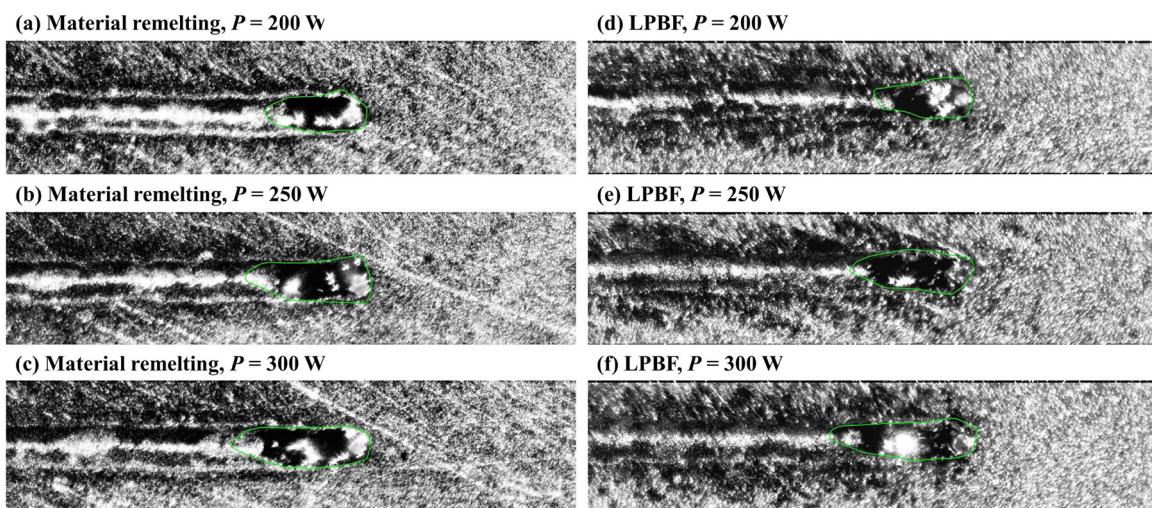


Fig. 10. Frame of supplementary video n.2 showing high-speed imaging acquisitions in different processing conditions and power levels. Molten pool contour identified by image processing algorithm in green. (a) Material remelting $P = 200$ W, (b) Material remelting $P = 250$ W, (c) Material remelting $P = 300$ W, (d) LPBF $P = 200$ W, (e) LPBF $P = 250$ W, (f) LPBF $P = 300$ W.

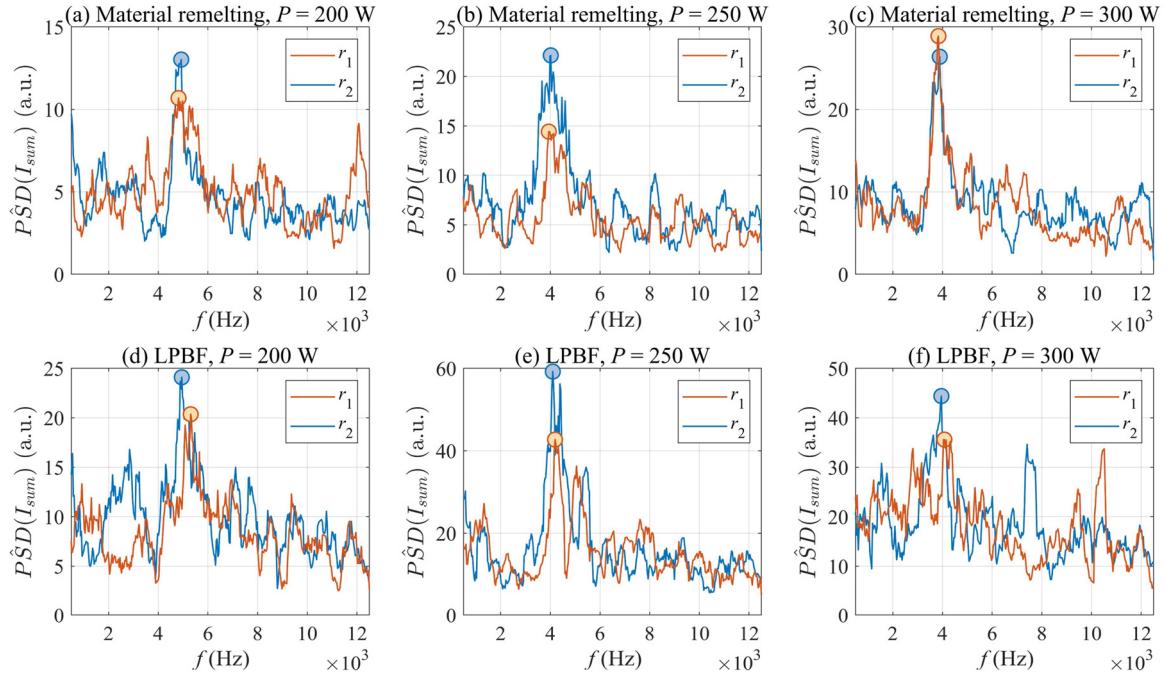


Fig. 11. PSD estimate of I_{sum} for material remelting (a)-(c) and LPBF (d)-(f) experiments. First replicate in blue, second replicate in orange. Peak values indicating oscillation frequency are shown by circular marker.

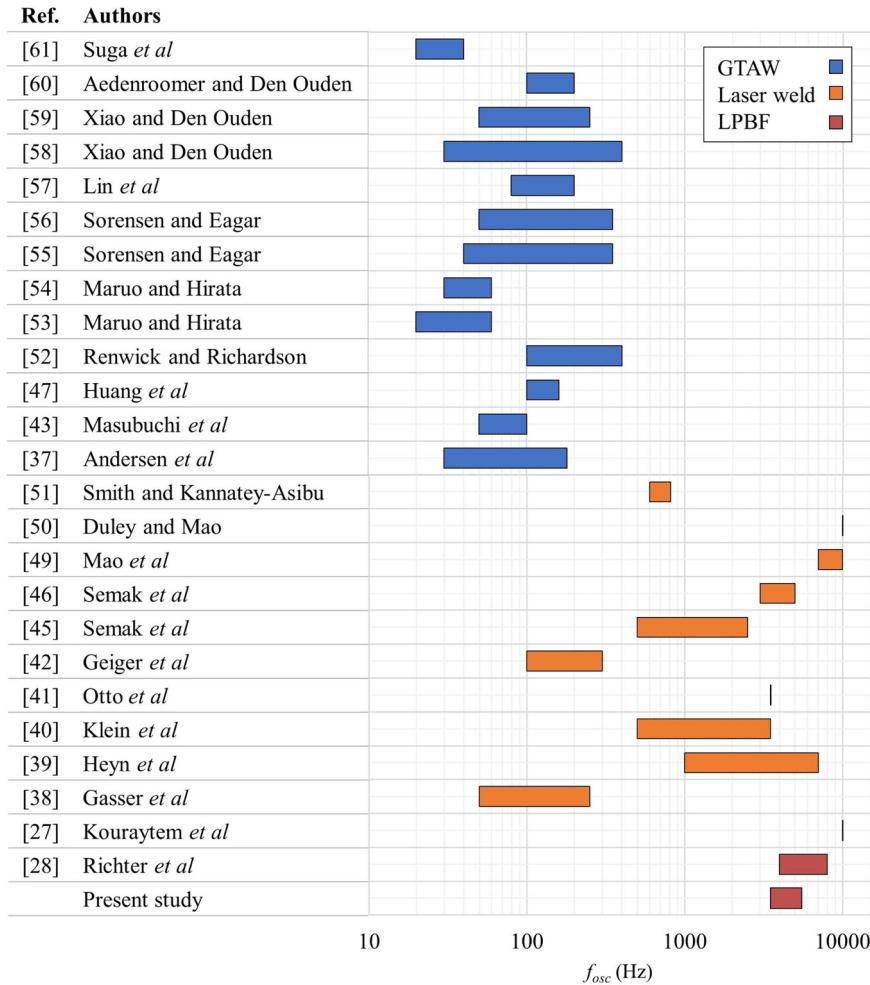


Fig. 12. Range of oscillation frequencies detected in literature and according to the present study. Categorisation according to the process (blue for GTAW, orange for laser welding and red for LPBF).

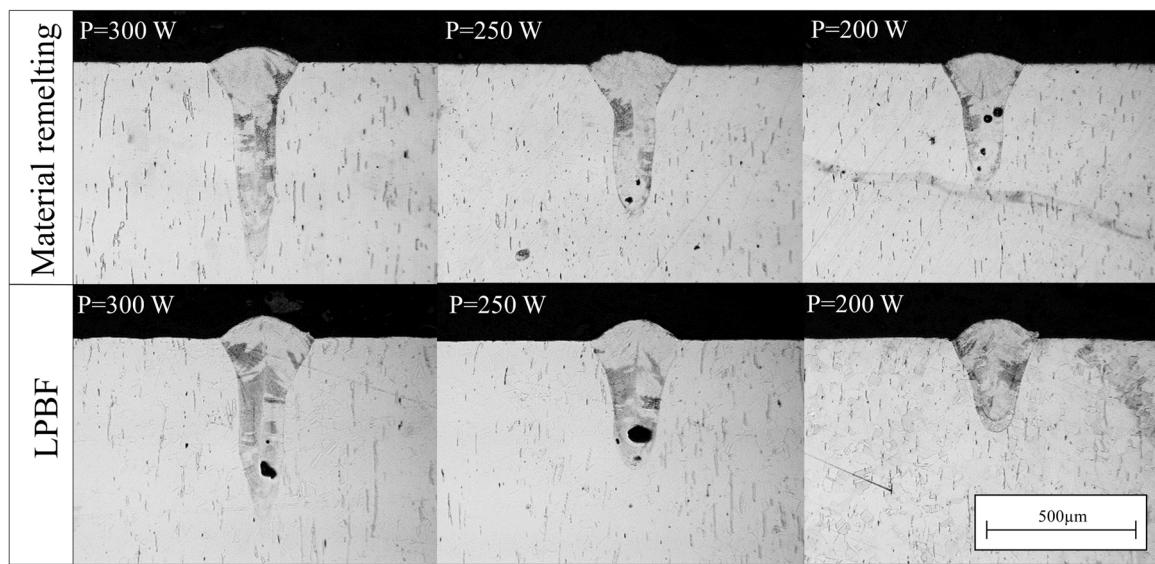


Fig. 13. Representative metallographic cross-sections of AISI316L bead-on-plate material remelting and LPBF depositions.

the difference between the LPBF and material remelting processes a more extensive experimental campaign with in conduction mode deposition conditions should be investigated. An apparently greater variability in the oscillation frequency may be denoted at $P = 200$ W (particularly for the LPBF track depositions). Still, this is consistent with the frequency resolution of the parametric PSD estimation method employed, implying that this might rather be an artefact.

4.3. Oscillation frequency - melt pool depth correlation

In Fig. 15(a) it is possible to view graphically the correlation between molten pool penetration depth and oscillation frequency while in Fig. 15(b) the relationship between cross-sectional area and f_{osc} is reported. These correlations can be related through statistical regression equations. Interestingly enough, it is possible to view how the

relationship between oscillation frequency and molten pool cross-sectional area is well-fitted ($R_{adj}^2 = 86.9\%$) by a model with a predictor $1/f_{osc}^2$. This supports the hypothesis that A_{cs} may be considered representative of the molten mass since this kind of relationship is typical of undamped mechanical systems. A statistical correlation between molten pool oscillation frequency and penetration depth may also be asserted (with a $1/f_{osc}$ predictor).

Further investigations are required in order to accurately identify the model which may coherently predict the process condition according to the observed phenomenon. Still, the results from the present investigation show that the oscillation frequency of surface waves may be employed as an indirect indicator of the penetration depth and other undisclosed parameters (such as molten pool mass). Process modelling, which will be conducted in future works, will allow to explore in greater detail the correlation between molten pool geometrical

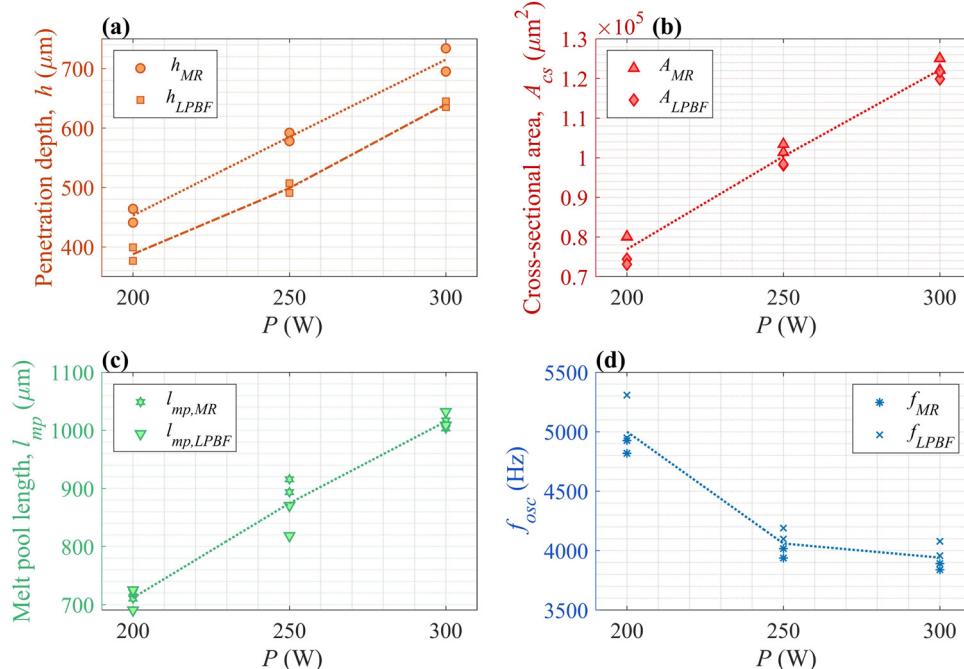


Fig. 14. Main effects trend and results as a function of emission power P for (a) penetration depth h , (b) cross-sectional area A_{cs} , (c) melt pool length l_{mp} and (d) oscillation frequency f_{osc} . Main effects lines have been added to enhance trend readability.

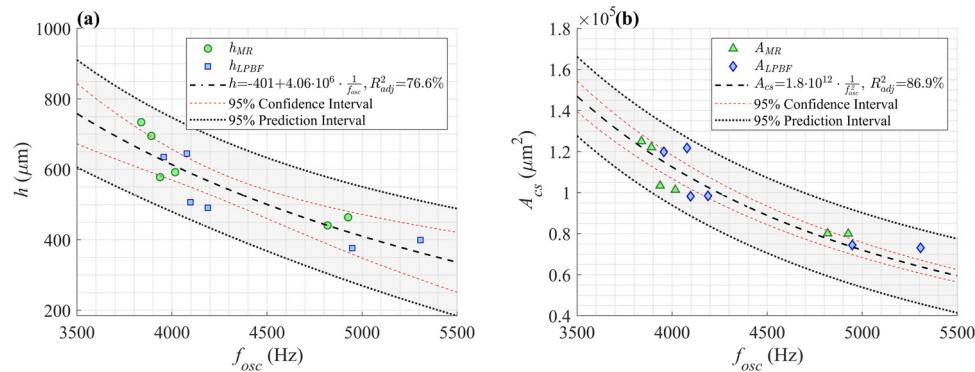


Fig. 15. (a) Penetration depth h against oscillation frequency f_{osc} and (b) cross-sectional area A_{cs} against oscillation frequency. Results in green for material remelting experiments, in blue for LPBF. Regression equation with confidence and prediction intervals indicated in both graphs.

indicators and oscillation frequency.

Overall, the results from this investigation are promising for the development of an in-situ monitoring tool which may enable the penetration depth estimation. Nonetheless, a series of aspects are to be taken into account. Firstly, the campaign currently developed was conducted from an off-axis configuration. Validation of the system by integrating the imaging system through a coaxial configuration is required. Although, it is possible to envision a solution of the kind, this would also imply the difficulties connected to the use of a coaxial illumination source [14]. Moreover, limitations in terms of data transfer rates for industrial applications would also require the use of integrated sensors filtered at the wavelength of illumination source (with the associated challenges connected to the absence of spatial information). Alternatively, a reduced ROI on a camera might ensure industrially applicable data transfer rates whilst complying with limits related to aliasing. At conventional LPBF processing conditions the molten pool will exhibit penetration depths slightly higher than the powder bed thickness. Hence, if the statistical relations of Fig. 15 hold, oscillation values around 8–10 kHz may be expected which are within the capabilities of these sensors.

Moreover, the current study reports results only for single track depositions. Validation for multitrack and multi-layer depositions are foreseen in future investigations. Further challenges for the proposed monitoring solution are derived by the compromises connected to the time-frequency analysis. In order to ensure a detailed oscillation frequency identification, a high resolution frequency and thus acquisition time are required. The present research configures as a preliminary investigation to demonstrate the possibility of correlating surface oscillations to the penetration depth also in the presence of powder. However, the scan speed employed is of an order of magnitude lower in comparison to values employed by industrial systems, thus implying that higher acquisition times would be needed to maintain a sufficient frequency resolution. If the observation time of the phenomenon is increased however, the distance travelled by the molten pool during this temporal framework would also increase hence resulting in a penalisation in the frequency with which the average molten pool depth estimate is obtained. Future works will concentrate on the best compromise to assess longer acquisitions in more conventional process regimes. The use of parametric Power Spectral Density estimates may allow for the use of shorter acquisition times and enhance obtainable frequency resolution but further studies are required to disclose these aspects.

The oscillatory motion is expected to be preserved even in typical processing regimes of the LPBF process where keyhole formation is undesired. Contributions to molten pool dynamics due to thermo-capillary forces, surface tension and recoil pressure are present also in conventional processing conditions. Without the keyhole, the molten pool will witness lower thermal gradients and recoil pressure fluctuations thus lower amplitude oscillations may be expected at higher

frequency (due to the smaller mass of molten material). Further investigations are underway to study these aspects in greater detail.

5. Conclusions

In the present investigation a methodology for the estimation of the molten pool penetration depth in the Laser Powder Bed Fusion process has been presented. The monitoring system devised relies upon the measurement of molten pool surface oscillations through reflections of a secondary probe light captured by means of a high-speed camera. An image processing algorithm and signal analysis procedure have been developed in order to extract an indicator representative of the oscillation frequency of melt pool surface waves.

Molten pool surface oscillations ranging from 3.5 kHz to 5.5 kHz were measured. At higher levels of emission power, the oscillation frequency of the molten pool decreases and may be directly correlated to an increase in molten pool mass and penetration depth. At constant process parameters, oscillation frequency did not show statistical difference between bead-on-plate and LPBF experiments. Both processes showed analogous trends with shallower melt pools at increasing values of the oscillation frequency.

Proof of concept testing of the devised methodology was conducted with both bead-on-plate material remelting and LPBF single track experiments. The monitoring equipment was designed and implemented in order to have sufficient spatial and temporal resolution as well as to obtain sufficient resolution in the frequency domain for the signal analysis procedure. Future work will look at investigating a wider range of experimental conditions and modelling of the process.

CRediT authorship contribution statement

Leonardo Caprio: Methodology, Conceptualization, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Ali Gökhan Demir:** Methodology, Conceptualization, Resources, Formal analysis, Writing - original draft, Writing - review & editing, Supervision. **Barbara Previtali:** Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

None.

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Appendix A

Within the following section the image processing code developed is presented. The high-speed imaging acquisitions must be post processed in order to extract geometrical and spatially distributed intensity information related to the molten pool. The frames acquired by means of the high-speed imaging setup can be analysed by means of self-developed code in Matlab environment. The aim of the code was to delineate the contours of the molten pool and extract indicators of interest to evaluate molten pool surface oscillations. The distortion introduced by the off-axis imaging set up was considered to introduce a negligible error due to the preliminary nature of the present investigation although it must be considered that a bias is introduced in the measurement of geometrical parameters of the molten pool such as width and area. Hence, the real image was not restored within the processing code developed. When operating on process emission images, it is possible to define the contours which are representative of the molten pool geometry, since it is sufficient to determine the value of a hard thresholding coefficient [4]. On the other hand, when observing directly the molten pool geometry through the use of a secondary illumination source, image processing is more complicated due to the presence of composite elements and grayscale values present in the image. Generally, the molten pool area may be identified by the localised values of black which are symptomatic of higher absorption of the illumination source [88]. Still, when the molten pool has a higher aspect ratio, this approach tends to be fallacious. Hence, a new algorithm for automatic identification of the molten pool was devised. The various image processing steps are shown successively in Fig. 6 and consist in:

- Background removal through the logarithmic difference of two successive frames. In this way the parts in motion of the image (i.e. the molten pool travelling over a fixed background due to the off-axis monitoring setup) are put in evidence. The obtained image will still present randomly distributed noise and other moving objects (for instance molten pool ejections or powder particles moving).
- Frequency filtering for melt pool area identification. A Butterworth high pass filter, generally employed for image sharpening applications, allows to enhance the edges of objects within an image. The frame was hence filtered in the frequency domain with a Butterworth high pass filter of order = 1 and cut off radius = 15. Result of this step may be viewed in Fig. 6(c).
- Hard thresholding for melt pool contouring (result shown in Fig. 6(d)). This step was conducted as a consequence of the previous high pass filtering in the frequency domain, in order to identify the contours of the molten pool. A lower threshold above 1 and a higher threshold set on an arbitrary value was employed to define the molten pool contour and obtain a binarized image. After this step, in Fig. 6(d), it is possible to denote the presence of salt-and-pepper noise and an ejected particle which must be removed prior to reconstructing the final molten pool boundaries.
- Median filtering for noise removal with a structuring element of size 5 pixel x 5 pixel. The frame after median filtering is shown in Fig. 6(e).
- Removal of molten pool ejections through successive dilation, area thresholding and erosion. The pixels with value 1 of the binarised image were dilated through the use of a rounded structuring

element of radius 10 pixel (as shown in Fig. 6(f)). The dilation step was done in order to interconnect neighbouring objects and fill voids within the identified molten pool. Then the objects within the image are filtered depending on their area. If the area of a specific object was 10 times smaller than the area of the structuring element it was discarded (post-processed frame shown in Fig. 6(g)). Successively the image is eroded by means of the same structuring element (shown in Fig. 6(h)). Finally, the eroded image is multiplied by the image prior to the image dilation so to preserve the original features of the frame after the frequency filtering step but removing the ejections (Fig. 6(i)).

- Melt pool boundary reconstruction. The positive values of the binarised image are transformed into x and y coordinates in order to employ the *Boundary* function available in Matlab programming environment (with a shrink factor of 0.1). This allows to interpolate the outer boundary of the cluster of points in Cartesian coordinates and thus generate a binarised image representative of the molten pool (as shown in Fig. 6(j) and (k)).
- Melt pool indicator extraction. Finally, using the *regionprops* function it is possible to extract the geometrical parameters of the molten pool (such as length, width, area etc.).

In the case of the bead-on-plate material remelting experiments the frequency filtering step is not necessary since the acquired images are not disturbed by the presence of the powder bed (i.e. the static background removal is more effective).

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.addma.2020.101470>.

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