A first quantitative approach for detecting volumetric defects in additive manufactured metal samples by using active thermographic technique

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Abstract. This work is focused on the quantitative analysis of defects produced in metal samples of AISI 316L with Laser Powder Bed Fusion (L-PBF) additive manufacturing (AM) process by means of active thermographic techniques. A simple and common set-up with 2 flash lamps and a cooled sensor has been used to analyse the differences between planar and volumetric defects. In particular, the presence of imprinted spheres containing inside non-sintered metallic powder has been compared with those of similar cylinders in size and depth, induced in similar samples. Furthermore, the differences in terms of thermal contrasts have been studied between the cylinder manufactured as an internal defect with powder inside, against the same geometry, but with a small channel for the discharge of the non-melted material. The analysis of the thermal signal and the application of post processing algorithms allowed us to identify the thermal features suitable for describing the behaviour of different kind of defects, typical of the process.

1. Introduction
Pulsed thermography is a fast, contactless, full field non-destructive technique used for detecting defects in composite and metals materials [1-8]. Commonly, it involves the use of flash heating lamps to inspect the surface and monitoring the thermal behaviour with an infrared camera, both during heating and cooling phases [1]. The most important applications include the detection and quantification of imposed defects, as flat bottom hole and inserts in composite materials to simulate delaminations and voids [1-8]. However, only few applications regard real defects [9-13], such as delaminations, impact damage, detachment, joint defects or even porosity, a typical and widespread defect especially in components produced using additive technology [9-10]. Recently, some works [9-10] demonstrated the capability of pulsed thermography to detect volumetric irregularly shaped defects, in comparison with micro computed tomography (μCT) investigation used as reference results.

As known, μCT is the more accurate NDT technique for characterizing volumetric defects, but it is time consuming and thus not suitable for industrial applications, as the additive manufacturing ones, in which many components need to be controlled [14-15]. However, it is known that diagnosing and quantifying a defect are two profoundly different things that are both necessary for obtaining the complete non-destructive control of components. Like all non-destructive testing techniques, thermography also needs calibration procedures, to define limits, advantages, and disadvantages of the techniques.
There are different works and references addressed to quantitative thermography, both for the depth [16-23] and the size characterization [24-26]. For the depth measurement, all the above-mentioned works are based on 1D models.

Lau et al. [16], following Carslaw and Jaeger’s solution [8], developed a relation for the surface temperature history of finite uniform thickness plate subjected to a Dirac pulse. Later, Almond and Pickering [17] modified the 1D analytical model to consider the finite size of defects, and then to obtain the prediction of peak contrast amplitudes and times for defects with different aspect ratios.

Starting from these models, the relationship between the decay of temperature on the inspected surface and time is widely used to estimate defects depth and many methods are based on the time [3] or frequency domain [5-6] analyses.

There are different methods that start from the study of the contrast between a sound and a defect area, such as the peak-slope time method (PST) and the Pulsed Phase Thermography (PPT). There are also methods without a reference point as sound area include, for example, logarithm second derivative method (LSD) [3], by means of the well-known algorithm of the thermal signal reconstruction (TSR), and the least-squares fitting method (LSF) [20-22].

These methods assume that the thermal wave reflection coefficient \( \gamma \) is 1, which is not true for most real situations [22], as the case of a volumetric defect or a defect failed with powder and not air. These methods have been validated in previous works by means of numerical simulations and experimental data on composite and plastic materials [20-22]. Moreover, these methods are greatly influenced by the noise and the amplitude of the thermal contrast, making the application more difficult in the case of metals and defects due to lack of fusion, typical of additives, with powder trapped inside.

In this work, a series of AISI 316L stainless steel samples were obtained by using the Selective Laser Melting (SLM) process, according to a complete plan, providing for the insertion of imposed defects of different types and sizes directly in the CAD. Two samples were printed with cylindrical defects inside, planar with respect to the examined surface, considering in the first case the creation of suitable channels to eliminate the non-fused powder trapped inside, while in the other one leaving it. On the other hand, in a complete second plan, twelve samples have been printed with internal volumetric defects of spherical shape, with dimensions (distance from the surface and maximum dimension) similar to those of the cylinders. Also in this case, the very compact unfused powder, of the same material, was left inside.

The aim of the work is to investigate the different thermal behaviour of planar and volumetric defects and the effect of the presence of unfused powder inside.

For this reason, the samples were inspected by means of pulsed thermography technique, using a set-up in reflection configuration with two flash lamps for a nominal energy value of 6 kJ and a cooled sensor. The material properties characterization required to assess the diffusivity value according to the ASTM standard applying the well-known Parker method [27].

The analysis of the raw thermal data has been carried out starting from the study of 1D thermal models present in the literature [17], studying the simple thermal signal and the defect-sound contrast and then applying the non-linear least-squares fitting method (NLSF). The raw thermal data were then post-processed, applying the well-known algorithm of the Pulsed Phase Thermography (PPT) [5-6], looking for the differences between a planar defect and a volumetric defect in the frequency domain and in particular in the depth – blind frequency correlation.

The obtained results show the lowest values for the reflection coefficient in the case of volumetric defects, and lower values comparing cylindrical defects with and without metal powder inside. The errors in evaluating both the size and depth have been calculated considering the nominal defect dimensions. The biggest errors (>20%) have been obtained for the volumetric defects, as expected, and, in general, for the defects with the smallest diameter (3 mm) and therefore far from the hypothesis of a large reflector.

2. Theory

In its simplest form, the pulsed thermographic technique in reflection configuration sees the typical configuration of one or two flash lamps and a microlometer or cooled sensor to stimulate the investigated material with a short and high energy light pulse and observe the thermal decay by means
of infrared thermography. A temperature response of an adiabatic semi-infinite body subjected to flash heating (theoretical Dirac pulse) is described with the well-known equation (1) [1]:

$$ T(0,t) = \frac{Q}{\sqrt{\pi \rho c k t}} \exp \left( -\frac{d^2}{4\alpha t} \right) $$

(1)

where $d$ represents the defect depth, $t$ is time and $T$ is the temperature value. $\rho$, $c$, $k$, $\alpha$ indicate the thermophysical material properties, respectively equal to density, heat capacity, thermal conductivity and the thermal diffusivity, equal in fact to the ratio $k/\rho c$. $Q$ takes into account the energy source for unit of surface transferred directly to the sample.

Following the models in [16], the presence of an inhomogeneity within the medium alters the transient temporal decay of temperature, depending on the difference of effusivities between the defect and the background material, and so directly according to the reflection coefficient $\gamma$. Specifically, the collected thermal decay is:

$$ T(0,t) = \frac{Q}{\sqrt{\pi \rho c k t}} \left[ 1 + 2 \sum_{n=1}^{\infty} \gamma^n \exp \left( -n^2 \frac{d^2}{4\alpha t} \right) \right] $$

(2)

Almond et al. [17], proposed a simple analytical model in which the effect of the defect aspect ratio on the signal contrast is considered, starting from the analysis of the thermal contrast between the defect and related sound area, over the centre of the detected defect:

$$ T_c(0,t) = \frac{2Q}{\sqrt{\pi \rho c k t}} \sum_{n=1}^{\infty} \gamma^n \exp \left( -n^2 \frac{d^2}{4\alpha t} \right) \left[ 1 - \exp \left( -\frac{(Pd)^2}{16\alpha t} \right) \right] $$

(3)

where $P=d/D$ is the defect aspect ratio, $m$ is the ratio of in-plane to through thickness thermal and $D$ is the diameter of a circular defect. Equation (3) can be used for estimating size (diameter) and depth of defects with a known aspect ratio and setting $\gamma=1$. However, equation (3) does not consider the shape or typology of defects.

Later, Sirikham et al. [21] proposed a modification that allows the equation (3) to be applicable to any segment of collected data. The proposed model is reported in equation (4):

$$ T_c(0,t+t_s) = \frac{2Q}{\sqrt{\pi \rho c k (t+t_s)}} \sum_{n=1}^{\infty} \gamma^n \exp \left( -\frac{(nd)^2}{\alpha(t+t_s)} \right) \left[ 1 - \exp \left( -\frac{D^2}{16\alpha(t+t_s)} \right) \right] $$

(4)

where $t_s$ is the starting time of sampling.

It is necessary to repeat that the analytical models in thermal NDT are typically 1D, and so they mainly refer to planar defects oriented in a parallel direction with respect to the sample surface [22]. In fact, the expressions above are approximate and allow for the correcting 1D analytical solutions by finite size of defect, typically flat bottom hole with different aspect ratio.

As known, the study of the simple thermal contrast doesn’t allow to characterize and quantify properly a defect, especially when this value is too weak, or the defect have a small aspect ratio.

For this reason, there are several algorithms of post processing used to improve the quality of the raw thermal data, and certainly the oldest one is the Pulsed Phase thermography (PPT), that allow to study the thermal response of the inspected surface in the frequency domain, passing through the appropriate use of the Discrete Fourier Transform (DFT), which is not always very simple to apply correctly. In particular, the correct application of this algorithm required the choice of the right truncation window size and the frame rate, to discretize the data in the correct way and by dividing the energy into the right number of components. Thanks to this type of analysis, it is therefore possible to have a rough estimation of the defect depth, considering the phase maps and the phase contrast for the detected defect. The main mathematical steps are enclosed in the following equations and in the last one, equation (7), which links the depth of the defect to the blind frequency, or the frequency for which the phase contrast is equal to zero, when the thermophysical properties of the material are known.

$$ \text{DFT } F_n = \Delta t \sum_{k=0}^{N-1} T(k\Delta t) e^{\frac{2\pi i nk}{N}} = \text{Re}_n + \text{Im}_n $$

(5)
\[
\text{phase } \varphi_n = \tan^{-1}\left(\frac{\text{Im}_n}{\text{Re}_n}\right)
\]

(6)

blind frequency \( d = C_1 \sqrt{\alpha \pi f_b} + C_2 \)

(7)

In these equations, \( i \) is the imaginary number, \( \text{Re} \) and \( \text{Im} \) are, respectively, the real and imaginary parts of the transform, and the subscript \( n \) represents the frequency increment. Phase maps are then computed with the equation (6), by repeating this process for all pixels. With \( N \) thermograms in the available sequence, \( N/2 \) frequency values can be obtained (due to the symmetry of the Fourier transform). Considering the sequence related to the phase maps, a detected defect and the related sound zone, it is possible to define the phase contrast and then the equation (7), that correlate the blind frequency \( f_b \) to the defect depth \( d \); here, \( C_1 \) and \( C_2 \) represent two calibration constants, and their value depends on the material properties and type of the defect.

3. Experimental setups and materials

3.1. Experimental setup and materials for the SLM process

A series of AISI 316L stainless steel samples (figure 1) were obtained by using a commercially available Concept Laser M1 Selective Laser Melting (SLM) machine. The latter is equipped with a Nd: YAG laser source characterized by a wavelength of 1064nm, a maximum laser power equal to 100W and a laser spot diameter equal to 200 \( \mu \)m. AISI 316L stainless steel powder, a commercial spherical powder with a particle size in the range of 15-53 \( \mu \)m, produced through gas atomization by Cogne Acciai Speciali S.p.a (Italy), was used as powder metal. Table 1 shows the nominal compositions of the powder as certified by the manufacturer.

![Figure 1. SLM samples.](image)

**Figure 1.** SLM samples.

**Table 1.** Chemical composition of the AISI 316L stainless steel powder (weight %).

| Alloying element | Cr       | Ni      | C   | Mn | Si  | S   | Mo  | N   | P   | O   | Cu  | Fe   |
|------------------|----------|---------|-----|----|-----|-----|-----|-----|-----|-----|-----|------|
| Nominal          | 16.0-18.0| 11.0-13.0| 0.03| 2.0| 0.75| 0.010| 2.0-3.0| 0.10| 0.025| 0.10| 0.50| Balance |

The samples were fabricated with defects of known sizes within them. As already said, two different shapes were chosen for the defects: spherical and cylindrical (figure 2). Some of the samples produced were manufactured with holes in the direction of the defects to allow the removal of the metal powder trapped in the defect during printing.
The samples were constructed with the same process parameters and scanning strategy optimized in previous studies [28-29]. A 5x5 mm² island scanning strategy was used (figure 3). The order in which these islands are scanned is random, a strategy patented by Concept Laser; the combination of these scanning factors allows to reduce the residual thermal stresses [30]. Samples were rotated 45° on the construction platform to avoid problems with powder coating from the blade. The process parameters considered as constant are presented in table 2.

Table 2. Process parameters.

| Parameter            | Unit | N | Value |
|----------------------|------|---|-------|
| Laser power          | W    | P | 100   |
| Scanning speed       | mm s⁻¹|  v | 200   |
| Laser spot diameter  | μm   | d | 200   |
| Layer thickness      | μm   | LT| 30    |
| Hatch distance       | μm   | h| 140   |

Figure 3. Random island scanning strategy: 5x5 mm² islands with scan angle variation of 90° between adjacent islands.

The experimental plan is resumed in the following tables (3, 4 and 5). It is necessary to point out that not all defects have been used in this work. The full analysis is intended for future work. In figure 4 are instead reported the technical drawings of the samples 2 and 3, used to show the intended geometry.
**Table 3.** Experimental plan, sample 1 – cylinders no powder (planar defects), diameters (D), depths (d) and defect aspect ratio (D/d).

| SAMPLE 1 (Cylinders no powder) | DIAMETER (D) [mm] | 8,00 | ASPECT RATIO (D/d) | DRILLED |
|---------------------------------|-------------------|------|-------------------|---------|
|                                 | 0,50              | 16,00|
| DEPTH (d) [mm]                  | 2,00              | 4,00 |
|                                 | 4,00              | 2,00 |
|                                 | 6,00              |      |
|                                 | 0,50              | 12,00|
| DEPTH (d) [mm]                  | 1,50              | 4,00 |
|                                 | 2,50              | 2,40 |
|                                 | 3,00              |      |
|                                 | 0,20              | 15,00|
| DEPTH (d) [mm]                  | 0,40              | 7,50 |
|                                 | 1,00              | 3,00 |

**Table 4.** Experimental plan, sample 2 – cylinders filled with powder (planar defects), diameters (D), depths (d) and defect aspect ratio (D/d).

| SAMPLE 2 (Cylinders filled with powder) | DIAMETER (D) [mm] | 8,00 | ASPECT RATIO (D/d) | Z LENGHT [mm] |
|----------------------------------------|-------------------|------|-------------------|---------------|
|                                        | 0,50              | 16,00|                   | 13,50         |
| DEPTH (d) [mm]                         | 2,00              | 4,00 |
| SIDE A                                 | 4,00              | 2,00 |
|                                        | 1,00              | 8,00 |
| DEPTH (d) [mm]                         | 3,00              | 2,67 |
| SIDE B                                 | 5,00              | 1,60 |
|                                        | 6,00              |      |
|                                        | 0,50              | 12,00|                   | 13,50         |
| DEPTH (d) [mm]                         | 1,50              | 4,00 |
| SIDE A                                 | 2,50              | 2,40 |
|                                        | 1,00              | 6,00 |
| DEPTH (d) [mm]                         | 2,00              | 3,00 |
| SIDE B                                 | 3,00              | 2,00 |
|                                        | 3,00              |      |
|                                        | 0,20              | 15,00|                   | 14,20         |
| DEPTH (d) [mm]                         | 0,40              | 7,50 |
| SIDE A                                 | 1,00              | 3,00 |
|                                        | 0,60              | 5,00 |
| DEPTH (d) [mm]                         | 0,80              | 3,75 |
| SIDE B                                 | 2,00              | 1,50 |
|                                        | 12,00             |      |
Table 5. Experimental plan, sample 3, 4 and 5 – spheres filled with powder (volumetric defects), diameters (D), depths (d) and defect aspect ratio (D/d).

| SAMPLE 3 x4 | SAMPLE 4 x4 | SAMPLE 5 x4 |
|-------------|-------------|-------------|
| **DIAMETER** (D) [mm] | 8.00 (D/d) | 6.00 (D/d) | 3.00 (D/d) |
| DEPTH (d) [mm] | SIDE A | SIDE A | SIDE A |
| 0.50 | 16.00 | 0.50 | 12.00 | 0.20 | 15.00 |
| 1.00 | 8.00 | 1.00 | 6.00 | 0.40 | 7.50 |
| 2.00 | 4.00 | 1.50 | 4.00 | 0.60 | 5.00 |
| 3.00 | 2.67 | 2.00 | 3.00 | 0.80 | 3.75 |
| 4.00 | 2.00 | 2.50 | 2.40 | 1.00 | 3.00 |
| 5.00 | 1.60 | 3.00 | 2.00 | 1.20 | 2.50 |
| DEPTH (d) [mm] | SIDE B | SIDE B | SIDE B |
| 5.00 | 1.60 | 2.80 | 2.14 | 2.00 | 1.50 |
| 4.50 | 1.78 | 2.30 | 2.61 | 1.80 | 1.67 |
| 3.50 | 2.29 | 1.80 | 3.33 | 1.60 | 1.88 |
| 2.50 | 3.20 | 1.30 | 4.62 | 1.40 | 2.14 |
| 1.50 | 5.33 | 0.80 | 7.50 | 1.20 | 2.50 |
| 0.50 | 16.00 | 0.30 | 20.00 | 1.00 | 3.00 |

Figure 4. Technical drawings reported as an example for the sample 2 (cylinders, planar defects) and sample 3 (spheres, volumetric defects).
3.2. Experimental setup for Pulsed Thermography

The experimental setup (figure 5) in reflection configuration used to perform the pulsed thermographic tests included a cooled sensor MWIR FLIR A6751 (FLIR Systems, Wilsonville, OR, USA) with a lens of 50 mm and a Hensel EH Pro 6000 (Hensel, Fairfield, NJ, USA) flash tube (optical pulse energy 6 kJ, pulse duration 3-5 ms). The main testing parameters are resumed in the following table. The contemporary need for a high frame rate and a good spatial resolution required the use of a no full frame window, with a consequent total number of tests equal to approximately 250, considering the complete plan and therefore the replicated samples.

Table 6. Main experimental setup parameters.

| Frame rate (Hz) | Acquisition time (s) | Calibration temperature range (°C) | Integration time (µs) | Windowing (pixels) | Spatial resolution (mm/pixel) |
|----------------|----------------------|-----------------------------------|-----------------------|--------------------|------------------------------|
| 600            | 10                   | 15.7-85 °C                        | 595.43                | 320x156            | 0.14                         |

Figure 5. Experimental setup: thermal source flash lamps and IR cooled sensor FLIR A6751.

4. Methodology and first results

4.1. 1D model and NLSF optimization procedure

As suggested in previous publications [20-22], it is possible to fit experimental data with the analytical solution using equation (3), choosing properly the number of variables and the variables themselves.

In this work, one of the main aims is to understand if the modification of the coefficient $\gamma$ can describe the behaviour of a volumetric defect, and if the powder inside the defect reduces its value.

Another question is related to the depth $d$ and diameter $D$ indicated as result or input parameters of the fitting, being the same variables in the case of a sphere, as a volumetric defect, based on the position of the pixels used and the cooling time analysed (truncation window size).

Besides, as already specified, the fitting required the previous assessing of the sound area and the defect one.

Here, considering the diagram and the result shown as an example in figure 6, a total area of 100 pixels is selected to evaluate the sound and 9 pixels for the defect area, then the thermal contrast is calculated, as represented in figure 6, passing from the thermal trends reported in figure 7 to the contrast, for the defects with the same nominal sizes diameter 8 mm and depth 0.5 mm, in the case of a cylinder without powder (blue line), a cylinder filled with powder (green line) and a sphere (red line). The figure 6 reports a thermal map taken, as an example, within the sequence at the time of maximum contrast.
Figure 6. Thermal contrast maps and diagram for sound and defect selection: (a) cylinder no powder, (b) cylinder filled with powder, (c) sphere filled with powder – D=8mm, d=0.5 mm.

Figure 7. (a) Thermal trends and (b) contrasts, considering cylinder no powder (blue line), cylinder filled with powder (green line), sphere filled with powder (red line) – D=8mm, d=0.5 mm.

In this study, the free parameters for the fitting will be $\gamma$, $D$, $d$ and $t_s$, following as model, the modification proposed by Sirikham et al. (equation 4), $m$ was assumed equal to 1, considering the material thermally isotropic, instead the number of iterations was assumed equal to 10, since the higher summing terms have appeared negligible. The fitting involved a precise and limited truncation window size of the raw thermal data, considering the signal relative to the standard deviation of the sound area, and therefore as the last frame the one for which the thermal contrast, taken at the centre of the defect, exceeded the chosen threshold by 2 times. To reduce the noise, a Gaussian filter equal to 1 was applied to the raw thermal data.

The NLF algorithm used the Matlab lsqnonlin least-square function to find the parameters, following an optimization procedure, following the equation (8):

$$
\min_{\gamma,D,d,t_s} T_{c\text{est}}(t)-T_{c\text{exp}}(t)
$$

considering the contrast between defect and sound, estimated $T_{c\text{est}}$ and experimental $T_{c\text{exp}}$. The values of $\gamma$, $d$, $t_s$, $D$ varied as follows:

$$
x_0=[0.6, 2.5x10^{-3}, 0.005, 5x10^{-3}];$$

$$l_b=[0.1, 0.2x10^{-3}, 0, 0.3x10^{-3}]; u_b=[1, 5x10^{-3}, 0.05, 8x10^{-3}]
$$

considering $x_0$ the initial value, and $l_b$ (lower band) with $u_b$ (upper band) the extremes of the chosen interval. The used model is the one reported in the equation (10), where the parameters left as free in the fitting are reported in square brackets:

$$
T_{c\text{[}\gamma,D,d,t_s\text{]}}=\frac{2Q}{\rho c\sqrt{\pi}a(t+t_s)}\left[\sum_{n=1}^{10}\gamma^n\exp\left(-\frac{(nd)^2}{a(t+t_s)}\right)\right][1-\exp\left(-\frac{D^2}{16\pi a(t+t_s)}\right)]
$$

The unknown parameters $Q/\rho c$ and $a$ are estimated, separately. In particular, for $Q/\rho c$, the same model reported in equation (10) was used, calibrating with the biggest defect in terms of aspect ratio,
with no powder inside, and therefore closer to the condition of the 1D model; in this case, the defect sizes are considered as known, and respectively equal to 8 mm for the diameter $D$ and 0.5 mm for the depth $d$, fitting only the portion of the curve between $t_s$ and the time of the maximum contrast, in order to have a correct estimate of the energy input $Q$.

For the rough estimation of the thermal diffusivity $\alpha$, reference was made to the ASTM standard [27], applying the Parker method, with a typical setup in transmission, cooled thermal camera and flash lamp, using a sample printed as per standard, of the same material with dimensions of 15x15x3 mm$^3$, averaging the result on 5 different tests.

4.2. Application of the Pulsed Phase Thermography (PPT) algorithm

The raw thermal data are then analysed, by means of the PPT algorithm. A truncation window size of 4096 is analysed, obtaining 2048 phase maps. The typical trend of the phase contrast is reported in figure 8, considering the defects with a diameter equal to 8 mm and a depth of 0.5 mm, in the case of a cylinder without powder (blue line), a cylinder filled with powder (green line) and a sphere (red line). As it is possible to appreciate from the reported zoom, the value related to the blind frequency is different, and it corresponds to a discrete value near to the theoretical one equal to 0. In this work, the value closest to 0 was automatically chosen by comparing the last negative and the first positive. 8 different defects are used to have an estimation of the constants $C_1$ and $C_2$, with the same nominal sizes, to calibrate the result and so to have a rough estimation of the defect depth.

![Figure 8. Phase contrast trends, considering cylinder no powder (blue line), cylinder filled with powder (green line), sphere filled with powder (red line) – D=8mm, d=0.5 mm.](image)

The quantitative analysis consists in estimating the depth ($d_{est}$) and diameter ($D_{est}$) of the defects with both methods, calculating the percentage error respect to the nominal values ($d_{nom}, D_{nom}$) and so the equation (11):

$$\text{%Error}_d = \frac{d_{est} - d_{nom}}{d_{nom}} \times 100; \ \text{%Error}_D = \frac{D_{est} - D_{nom}}{D_{nom}} \times 100$$

(11)

5. Quantitative results and discussion

5.1. 1D model: assessing the reflection coefficient value and defect sizes estimation

Following what is reported in the previous paragraph 4.1, some of the available thermographic data have been analysed by means of the NLSF method. As mentioned above, the use of the NLF technique requires a priori knowledge of material thermal diffusivity, that was evaluated using the Parker method considering a sample with standard dimensions and obviously of the same material and lot of powder. After five different measurements, considering an average area in the middle of the sample
with homogeneous and uniform heating, and so the mean and standard deviation value of the same, the estimate obtained is in any case in the range of the literature and equal to $3.25 \times 10^{-6} \pm 0.02 \frac{m^2}{s}$.

Following the equation 11 and the NLSF method, it is possible to obtain an estimation of the energy input for this material, equal to $\frac{Q}{\rho c} = 0.0015 [K*m]$, with a contrast trend over the defect centre and the relative fitting shown in figure 9. For this case, the reflection coefficient value was determined by fitting equal to $\gamma = 0.84$.

**Figure 9.** Contrast trend (cyan line), data used for the fitting with NLSF method (blue points) and result of the fitting considering the case of a cylinder with no powder – D=8mm, d=0.5 mm.

The 1D model application concerns the defects visible from the analysis of the thermal contrast, in any case with a value higher than 2 times the standard deviation of the relative sound signal. The result for the empty cylinders is reported in figure 10, for the cylinders filled with powder in figure 11, while for the spheres in figure 12. As it is easily to see, the chosen criterion allows a better fitting for lower contrasts.

**Figure 10.** Contrast trends (marker lines) and fitting result by means of NLSF method (solid line) – cylinder no powder.
Figure 11. Contrast trends (marker lines) and fitting result by means of NLSF method (solid line) – cylinder filled with powder.

Figure 12. Contrast trends (marker lines) and fitting result by means of NLSF method (solid line) – spheres filled with powder.

The following table 7 instead summarizes the main results of the fitting, as comparative indexes to distinguish the types of defects and to have an estimation of the errors carried out in determining their size.

Table 7. Quantitative results in size estimation by means of NLSF method.

| Nominal depth ($d_0$) [mm] | Nominal Diameter ($D_0$) [mm] | γ  | Estimated depth ($d$) [mm] | $t_1$ [s] | Estimated Diameter ($D$) [mm] | % depth error | % Diameter error | $R^2$ |
|---------------------------|-----------------------------|----|--------------------------|--------|-----------------------------|-------------|----------------|-------|
| 5,00E-04                  | 8,00E-03                    | 0.69 | 4,32E-04                | 0.00  | 7,66E-03                 | -13.55      | -4.19         | 0.86 |
| 5,00E-04                  | 6,00E-03                    | 0.65 | 4,22E-04                | 0.02  | 6,24E-03                 | -15.63      | 3.98          | 0.84 |
| 1,50E-03                  | 6,00E-03                    | 0.65 | 1,38E-03                | 0.00  | 6,10E-03                 | -7.68       | 1.75          | 0.93 |
| 2,00E-03                  | 8,00E-03                    | 0.62 | 1,93E-03                | 0.05  | 8,00E-03                 | -3.37       | 0.00          | 0.96 |
| 4,00E-04                  | 3,00E-03                    | 0.63 | 2,56E-04                | 0.00  | 3,55E-03                 | -35.94      | 18.35         | 0.78 |
By means of the reflection coefficient $\gamma$, it is possible to discern the thermal behaviour between metal-air $\gamma = (0.7/0.6)$, metal-powder metal $\gamma = (0.6/0.5)$. This difference is even more evident in the case of the spheres (metal-powder metal) $\gamma = (0.4/0.3)$.

The higher errors (>20%) in the estimation of the sizes are obtained in the case of spheres or also planar defects with lower diameter (3 mm), because they are further away from the hypotheses of 1D model, and they are highlighted in yellow in Table 7.

The column of the errors committed in estimating the diameter in case of volumetric defects is left blank because the size depends on the section of the sphere and therefore from the analysed truncation window size.

5.2. Quantitative results by means of the application of the Pulsed Phase Thermography (PPT) algorithm

The raw thermal data have been processed by means of PPT. The analysis returns different phase maps in the frequency domain with result quality and thermal resolution that depends on the testing and analysis parameters, and in particular on the frame rate and the truncation window size.

Each frequency result of this analysis theoretically refers to a precise defect depth, and the two quantities are inversely proportional. It follows that for each frequency, in the case of a planar defect, there is always the same thermal imprint, as shown for example in figure 13 (a, b, c) for the defect with sizes $D=8\,\text{mm}$ and $d=0.5\,\text{mm}$ considering 3 different frequencies. Instead, in the case of a volumetric defect, the typical result is the one reported in figure 13 (d, e, f), for the same frequencies and the sphere with the analogous sizes of the previous cylinder.

Considering a profile in both directions (figure 13 a, with white lines), it is possible to recognize the same typical trend, therefore characteristic of planar defects and volumetric defects. This effect is obviously less pronounced for small defects. Figure 14 reports the case for planar and volumetric

| $f=0.59\,\text{Hz}$ | $f=1.46\,\text{Hz}$ | $f=3.22\,\text{Hz}$ |
|---------------------|---------------------|---------------------|
| (a) cylinder        | (b) cylinder        | (c) cylinder        |
| (d) sphere          | (e) sphere          | (f) sphere          |

Figure 13. Phase maps for 3 different frequencies and in the case of a cylinder filled with powder and the analogous sphere $D=8\,\text{mm}$, $d=0.5\,\text{mm}$; (a) $f=0.59\,\text{Hz}$ – cylinder, (b) $f=1.46\,\text{Hz}$ – cylinder, (c) $f=3.22\,\text{Hz}$ – cylinder, (d) $f=0.59\,\text{Hz}$ – sphere, (e) $f=1.46\,\text{Hz}$ – sphere, (f) $f=3.22\,\text{Hz}$ – sphere.
defects filled with metal powder, considering 3 different diameters (8 mm, 6 mm and 3 mm) and 3 different depths (0.5 mm, 0.5 mm and 0.2 mm).

![Graphs showing phase trends for different frequencies and defects.]

**Figure 14.** Phase trends for 6 different frequencies and in the case of cylinders filled with powder and the analogous spheres for 3 different dimensions; (a) cylinder D=8 mm, d=0.5 mm, (b) cylinder D=6 mm, d=0.5 mm, (c) cylinder D=3 mm, d=0.2 mm, ; (d) sphere D=8 mm, d=0.5 mm, (e) sphere D=6 mm, d=0.5 mm, (f) sphere D=3 mm, d=0.2 mm.

Finally, it is possible to note a characteristic thermal trend for the two types of defects by plotting the surface at a certain frequency. There is therefore a phase contrast with an almost constant value for the entire surface of the defect, showing an example in figure 15 a for the cylinder filled with powder D=8 mm – d=0.5 mm, and the analogous sphere figure 15 b with a phase peak in the centre of the defect, considering obviously the same scale.

![Phase surface maps showing examples of defects.]

**Figure 15.** Phase surface maps in the case of a cylinder filled with powder (a) and the analogous sphere (b) D=8mm, d=0.5 mm for a f=1.46 Hz.

Considering the equation 6 and so the phase contrast trends for 8 different defects (see table 8 and rows 1 and 2 for the nominal sizes) and all the cases (cylinders without powder (blue line), cylinders filled with powder (green line) and spheres (red line)), the blind frequency value for each defect was assessed, following the criterion explained in the section 4.2. The calibration curve (equation 6) seems to be different changing the defect type, and in particular the calibration constant C₂. The constant C₁ is instead very similar and in fact the calibration curves are almost parallel.
Figure 16. Calibration curves by means of PPT (equation 6); cylinders without powder (blue line), cylinders filled with powder (green line) and spheres (red line).

The errors carried out in estimating the defect depths by means of the previous equations and the calibration curves are reported in table 8, with their respective colours. Again, the highest errors (>20%) are recorded in the case of volumetric defects and for the smallest planar defects, especially when the wrong curve is used to determine the error on the depth (the type of defect is not always known a priori). The obtained curves are logically still valid for the defects not considered for the calibration, as reported for example in last column of the table 8, in bold.

| Nominal Diameter (Dn) [mm] | 3,00E-03 | 6,00E-03 | 6,00E-03 | 6,00E-03 | 8,00E-03 | 8,00E-03 | 3,00E-03 | 3,00E-03 |
|----------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| Nominal depth (dn) [mm]    | 2,00E-04 | 2,50E-03 | 1,50E-03 | 5,00E-04 | 2,00E-03 | 5,00E-04 | 4,00E-04 | 1,00E-03 |
| Estimated depth (d) [mm]   | 2,48E-04 | 2,41E-03 | 1,37E-03 | 5,29E-04 | 2,14E-03 | 5,11E-04 | 3,17E-04 | 1,07E-03 |
| % depth error              | 24,23    | 3,48    | 8,77    | 5,72    | 7,24    | 2,27    | 20,68   | 6,81    |
| Estimated depth (d) [mm]   | 3,24E-04 | 2,34E-03 | 1,64E-03 | 5,00E-04 | 2,14E-03 | 4,95E-04 | 4,39E-04 | 1,19E-03 |
| % depth error              | 82,15    | -6,46   | 9,60    | 0,08    | 7,24    | -1,06   | 9,82    | 18,86   |
| Estimated depth (d) [mm]   | 5,07E-04 | 2,47E-03 | 1,77E-03 | 5,83E-04 | 2,14E-03 | 4,94E-04 | 5,93E-04 | 1,21E-03 |
| % depth error              | 153,44   | -1,06   | 18,08   | 16,54   | 6,85    | -1,25   | 48,24   | 20,68   |
| Estimated depth (d) [mm]   | 4,35E-04 | 2,44E-03 | 1,72E-03 | 5,13E-04 | 2,10E-03 | 4,22E-04 | 5,23E-04 | 1,15E-03 |
| % depth error              | 117,71   | -2,41   | 14,94   | 2,58    | 4,84    | -15,55  | 10,83   | 14,89   |
| Estimated depth (d) [mm]   | 3,38E-04 | 2,37E-03 | 1,64E-03 | 4,16E-04 | 2,02E-03 | 3,24E-04 | 4,27E-04 | 1,06E-03 |
| % depth error              | 68,84    | -5,24   | 9,58    | -16,76  | 1,07    | -35,14  | 6,69    | 6,08    |

The analysis of the error will be the subject of future works and thanks to replicated samples, it will allow us to obtain the confidence bands and the other defects available in the experimental plan.

The results demonstrate the importance of adopting a suitable calibration procedure for obtaining an accurate estimation of the size and depth, above all for volumetric defects.
6. Conclusions and outlooks

The main conclusions of this work can be summarized by the following bulleted list:

- Assessment of quantitative indexes to discern the thermal behaviour between metal-air \( \gamma = (0.7/0.6) \), metal-powder metal \( \gamma = (0.6/0.5) \);
- Assessment of quantitative indexes to discern the thermal behaviour between planar \( \gamma = (0.7/0.5) \) and volumetric defect \( \gamma = (0.4/0.3) \);
- Evaluation of the errors done in defects characterization by using 1D methods (1D model with the diameter correction and the blind frequency-PPT);
- First indication to define the limit of detection of volumetric defects by active thermography \( \frac{D_{\geq 6}}{D_{=2.5}} = 2.4 \), \( \frac{D_{=3}}{D_{=1}} = 3 \) and the adopted set-up \( \rightarrow 2 \) flash lamps \( \frac{Q}{\rho c} = 0.0015 \) [K*m], MWIR cooled thermal sensor 600 Hz, acquisition time 7s.

The results presented in this first work are to be understood as preliminary results of a larger activity, which aims to the following future developments:

- Completing all the analyses provided for in the experimental plan and evaluating the probability of detection (POD) for volumetric defects by means of different algorithms;
- Carrying out a FEM model to study the 3D effects produced by the volumetric defects on the thermal signal comparing with the experimental tests (detection limit for volumetric defects);
- Using volumetric defects for calibrating the thermographic data and then quantifying porosity as typical defects of metal additive manufacturing (micrographic analysis as a reference).

Conflicts of Interest: the authors declare no conflict of interest.

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