The absence of on-line monitoring and process quality assurance is one of the main obstacles for wide implementation of Selective Laser Melting technology in modern manufacturing industry. Temperature monitoring in the laser impact zone are carried out by an originally developed bi-colour pyrometer and CCD camera which are integrated with the optical scanning system of the PHENIX PM-100 machine. Experiments are performed with variation of basic process parameters such as powder layer thickness (0-120 µm), hatch distance (60 µm-1000 µm), and fabrication strategy (the so-called “one-zone” and “two-zone”).

Keywords: optical monitoring, selective laser melting, pyrometry, CCD camera, high temperature.

1. Introduction

Modern Selective Laser Melting (SLM) systems are intended for melting a wide range of powder materials with greatly different properties, including melting point. Therefore the technological windows (i.e. optimum values of laser power, beam scanning speed, powder layer thickness, etc.) are rather different for different powders. The fabrication of a part with complex form and relatively large size can continue during 10 - 20 hours without any information about work in progress and possible problems. Typically the SLM process is carried out in closed environment without optical access for diagnostic equipment.

SLM is a repetitive stepwise process [1-7] (fig. 1): (a) A thin layer of powder is spread over a building substrate; (b) a laser beam selectively scans and fuses powder reproducing cross-sections generated from a 3D CAD digital model; (c) after a cross-section is fused, the powder bed is lowered, a new layer of powder is applied on top, and the process is repeated. Superposition of multiple cross-sections ultimately results in the desired solid 3D object.

To obtain the required geometry and structure of an object throughout a long-time fabrication cycle, consistent SLM conditions must be applied [8]. While manufacturing a part,
substrate; the uniformity of energy deposition in powder over the depth; and widening the energy deposition spot relative the incident laser beam. An important fraction of the laser energy absorbed directly by the substrate is favourable for formation of a metallurgical contact between the remelted powder and the substrate [13]. The depth and the width of the zone of laser energy release define the spatial resolution of SLM. Experimental studies of the reflection of the laser radiation by powder beds [14, 15] indicated that the absorbance of powder is considerably higher than the absorbance of the same material in the dense form.

The total absorbance of the system composed of a powder layer and a substrate of the same material on which the powder is deposited increases with the layer optical thickness and the absorptivity of the solid phase. The fraction of the incident radiation absorbed by the substrate decreases with the optical thickness of the covering powder layer and can have a local maximum as the function of the absorptivity of the solid phase [16]. The radial transport of the radiative energy due to scattering of the incident laser beam in the powder layer can considerably reduce the intensity of heat source at the centre of the beam. The widening of the radial profile of the deposited energy is less important. The whole energy efficiency of laser treatment and the heating of the substrate decrease with the reflectivity of the material. However, more uniform heating of the powder layer can be attained at higher reflectivity.

The basic objective of on-line process control in SLM is to assure quality of the developed parts and to optimise various stages of the process, for example to minimise the undesirable deviations from the required geometry and mechanical properties. To reach the goal, it is necessary to elaborate methodology and produce optical and electronic equipment for comprehensive process control using different and complementary diagnostic tools. "Integral" characteristic of such system consists in the fact that it should monitor the whole sequence of manufacturing steps and inspect the built-up object throughout the entire manufacturing cycle. The integral process control/product quality inspection (IPC/PQI) system is intended:

- to set up optimal laser beam parameters prior to the manufacturing process;
- to control laser beam parameters in course of manufacturing;
- to permanently monitor quality of the powder layering;
- to examine the result of laser action onto the powder layer, i.e. fusion quality;
- to inspect on-line the built-up object in terms of geometric conformity, details accuracy.

The above mentioned objectives are realized only partly at present [17-21] and the paper is focused on application of a pyrometer and a CCD camera for monitoring of thermal processes in SLM and comparison of the results obtained by different diagnostic tools.

2. Experimental set-up

Non-contact optical methods are most suitable to reach the goal. It is supposed that the temperature value in the laser impact zone is rather sensitive to detect deviation of the SLM parameters from their optimums. For example, variations of the temperature and its instability will indicate that the energy input per unit length in the beam scanning strategy should be changed.

To exclude the influence of the scanning speed, observations must be carried out coaxially to the laser beam. In this case, for any position of the laser beam and for any scanning speed, the diagnostic system will register the signal from the processing zone.

![Figure 2. Schematic of the optical system applied: 1- fiber laser; 2- beam expander; 3- laser beam /thermal signal separating mirror; 4- scanner head; 5- F-Theta lens; 6- powder bed; 7- mirror; 8- pyrometer lens; 9- fiber tip; 10- optical fiber; 11- pyrometer; 12- CCD camera.](image)

In order to continuously monitor the surface temperature, i.e. temperature in the laser impact zone, a two-wavelength pyrometer (11, fig. 2) registering surface thermal radiation is connected to the optical unit by an optical fiber (10, fig. 2). In parallel, the CCD camera (12) measures thermal radiation from the heat affected zone (HAZ) that is much larger than the laser spot size.

3. Data acquisition

Pyrometer

Temperature was measured in the laser impact zone by an originally developed bi-colour pyrometer with the following performance: temperature range is 1200-2900 K, two InGaAs photodiodes with optical filters, transmission spectrum at central wavelength 1.26 µm with 100 nm bandwidth, 560 µm diameter of the zone of temperature measurements. The signal integration time is 50 ms with sampling time equals to 50 µs. At present, arbitrary units are used instead of the temperature values because of the following reasons: For correct pyrometric measurements, the zone of characteristic temperature variations must be larger than the pyrometer view field. In this study, the laser spot was 70 µm diameter that resulted in about 100-120 µm width of the remelted powder track. The 400 µm diameter optical fiber was used to avoid chromatic aberrations in the diagnostic system. Image magnification after passing through the optical system of the SLM machine (fig. 2): F - Theta lens (5), mirrors (3, 7) and pyrometer lens (8) is 1.4 times that provides the pyrometer observation zone of 560 µm diameter (fig. 3). That is why the results of pyrometric measurements for wavelength λ =1.26 µm are presented here in arbitrary units.
CCD camera

Brightness temperature distribution in the HAZ was acquired by the CCD camera (12, fig. 2) with a resolution of 560x760 pixels. The brightness temperature measurements were realized with the exposition time of 3 ms.

To obtain the brightness temperature, the CCD camera was calibrated using a W - halogen lamp with a transmitting diffuser. The W - halogen lamp was calibrated with a black body in the temperature range from 1200 to 1800 K.

Transversal and longitudinal profiles of brightness temperature captured by the CCD camera were obtained after treatment and averaging of 5 consecutive images. The values of brightness temperature used in figs. 6b, 10 correspond to the maximum temperature value in the heat affected zone.

For a further discussion, it is necessary to introduce a definition of a “track” and a “hatch distance”. A track is the result of the laser beam scanning along a straight line on the powder bed with a constant speed. Hatch distance, \( \delta \), (fig. 4d) is the distance between the neighbour tracks.

4. Process parameters

The experiments were carried out on Phenix PM100 machine (see SLM schematic in fig. 1). Laser source is YLR-50 a continuous wave Ytterbium fiber laser by IPG Photonics operating at 1075 nm wavelength with \( P = 50 \) W maximum output power.

In the present study, 32 W power was delivered to the powder layer. The laser spot size on the surface of the powder bed is 70 µm in diameter. Inox 304L 98 mm diameter plates are used as building substrates. The fabrication module provides a closed environment with protective atmosphere of pure nitrogen.

Unless otherwise stated, the following parameters were applied: laser beam scanning speed, \( v \), is 120 mm/s, hatch distance, \( \delta \), is 120 µm, zone of beam scanning is a square 10x10 mm². Inconel 625 (-22 µm) powder was used.

5. Results and discussion

5.1 Laser scanning of steel substrate without powder

To illustrate the purpose of applying optical diagnostics for the SLM process, experiments were particularly aimed to register the superposition of thermal processes in the consequent tracks during laser scanning. A clean substrate of stainless steel with regular linear surface roughness \( R_a = 3.2 \) µm was used.

Consider heat processes during laser beam scanning of a rectangular. Duration of a single line (10 mm) scanned by the laser beam is 83.3 ms. During this time, the heat is spread over 660 µm (heat affected zone is estimated as \( \sqrt{a \cdot (L/v)} \), where \( L \) is the track length, \( v \) is the beam scanning speed, and \( a \) is the temperature diffusivity of substrate) that is larger than the hatch distance (120 µm). That is why the next laser track will pass through the heat affected zone of the previous one. By superposition of the heat affected zones from a number of individual tracks, a macroscopic temperature field is formed with a maximum temperature close to the central part of the rectangular and lower temperature at its periphery. One may note the increase of the mean pyrometer signal with time in fig. 5. Indeed, after laser scanning, 10x10 mm² of substrate surface had 246 J energy input. Because of the chosen beam scanning strategy, all the tracks are started from one and the same side of the rectangular where temperature will be lower compared to the opposite side where tracks are finished. This is because of the transient period of heating at the beginning of each track. One can resume that the laser beam is crossing a non-uniform macroscopic temperature field which is superposed with its proper “microscopic” temperature field.
The interval between consecutive temperature measurements (50 ms) is comparable with the time of a single line scanning (83 ms). This results in the following. Supposing that the current pyrometer measurement is done at the middle of the track (where contribution of the macroscopic temperature field is the highest), then the next measurement will be carried out 50 ms later that corresponds to about 8 ms after the beginning of the next line scanning (where contribution of the macroscopic temperature field is the lowest). As a result, the two consecutive measurements will provide different results. This is the reason of the oscillations of the pyrometer signal. One may note that the period of oscillations is close to 113 ms (results of Fourier analysis of the pyrometer signal) that corresponds to the double of the pyrometer sampling time. Indeed, if the current measurement is done somewhere in the middle of the track that provides “maximum” temperature, then the next measurement will be done at the beginning of the next track that will correspond to the “minimum” temperature, and the third measurement will be done about 60 ms after the beginning of the track scanning that one more time will provide “maximum” temperature.

5.2 Variation of hatch distance using thin powder layers

The hatch distance is one of the most significant parameter influencing the quality of the parts fabricated by SLM technology [3, 8]. Experiments were carried out with a 50 µm powder layer thickness and variation of the hatch distance, δ, from 70 µm up to 160 µm.

Several 10 x 10 mm² square areas were scanned by the laser beam using the same strategy as in chapter 5.1. The average value of the pyrometer signal and brightness temperature measured by CCD camera corresponding to the total scanning duration for one square were defined, as well as the range of deviations from the average value.

That is why each experimental point from fig. 6a,b corresponds to the scanning of the same square but with different hatch distances.

The increase of the average pyrometer signal during square scanning, similar to the one presented in fig. 5, was not detected when powder was deposited on the substrate, that could be explained by lower heat input into the substrate because of the energy consumed for powder melting.

In general, the temperature in the zone of laser action and the pyrometer signal depend on the heat loss into the substrate. That is determined by the contact area of the laser heated material and the cold substrate. Three zones can be distinguished in figure 6:

- In the first zone (δ is up to 105 µm), a consecutive track is so close to the previous one that they form direct metallurgical contact. The actual melt pool interacts with the previous track and the substrate resulting in significant heat losses. The transversal temperature profile width and the heat affected zone length are presented in fig. 7 a,b.
The second zone (δ varies from 105 µm up to 120 µm) is characterized by the signal rise because the melt pool is no more in contact with the previously fabricated track. The volume of remelted powder increases with the

In the third zone (δ is larger than 120 µm), interaction between the tracks is practically absent, and the volume of remelted powder per single track reaches maximum and constant value. Further slight decrease of the pyrometer signal with hatch distance is explained by lower energy input into the substrate when scanning the fixed surface of the squares by smaller number of laser tracks. The length and the width of the heat affected zone increases with hatch distance (curve 3 in fig. 7a,b).

5.3 Variation of the hatch distance using thick powder layers

10×10 mm² square on the surface of a 1 mm thick powder layer was scanned by the laser beam with hatch distance varying from 70 µm up to 1000 µm.

The particular feature of these experiments is that the tracks have no metallurgical contact with the substrate.

Surface structures presented in fig. 8 were fabricated by laser beam scanning of the 10×10 mm² square at the same conditions but different hatch distances δ. The scanning speed v = 120 mm/s, the laser power P = 32 W, and the layer thickness 1 mm were constant. Note that beam scanning direction was always the same, i.e. vertical, for all samples presented in fig. 8.

For the entire ranges of the hatch distances, δ, applied, the first laser-scanned track results in separate spheres about 240 µm in diameter formed along the scanning direction. This phenomenon is driven by the Plateau–Rayleigh instability, often just called the Rayleigh instability, which provokes the disaggregation of the molten pool and the sphere formation under capillary force. For hatch distances δ = 300 µm and 1000 µm (Fig. 8e,f), zones of non-melted powder existed between the tracks, for example, the width of such zone was 60 µm for δ = 300 µm.

With the decrease of the hatch distance δ a contact appears between the track already melt in the form of separate spheres and the molten pool of the next track. In this case, the droplets of melted powder of the currently processed track stick to the spheres of the previous one. Thus, a structure perpendicular to the scanning direction is formed (Fig. 8a,b,c,d). This is a kind of self-organised surface structuring.

Evolution of the pyrometer signal versus hatch distance is presented in fig. 9.

The total scanning duration depends on the number of tracks which is defined by the hatch distance. This is why the durations of the thermal cycles in fig. 9 are different: the smaller the hatch distance, the greater is the number of tracks and the total duration of the scanning of 1 cm².

Generally, increase of the pyrometer signal with the decrease of the hatch distance (Fig. 9) is the result of the difference in energy input into 1 cm².

Thermal interaction between the tracks under the conditions of absence of metallurgical contact with the substrate could be described as follows:

• For the hatch distance less than 180 µm (fig. 7(a),(b),(c) and fig. 9 curves 4-6), the tracks are fused to one another forming a thin square object detaching from the substrate. At the beginning of the pyrometer registration, a significant increase of the signal is observed. This is caused by the heat accumulation in the previously fabricated tracks because of low heat loss into the surrounding powder layer. Further stabilization of the signal is related to the increase of the size of the fabricated object and an intensive heat transfer into it from the track under fabrication.

• In the case of the hatch distance from 180 µm up to 300 µm (fig. 8(d),(e) and fig. 9 curves 2,3), the neighboring tracks are separated by the powder. The pyrometer signal is stable during the whole laser scanning cycle. The heat transfer takes place through the powder situated in between the individual tracks.

• For a large hatch distance δ = 1000 µm (fig. 8(f) and fig. 9 curve 1), the pyrometer signal represents the formation of individual tracks when no interaction between them occurs.
5.4 Variation of powder layer thickness

Powder layer thickness is another important technological parameter of SLM. Relatively small thickness (minimum 20 µm) results in high accuracy of fabrication but low productivity, and vice versa.

The increase of the pyrometer signal and maximum value of brightness temperature measured by CCD camera in the HAZ with powder layer thickness (figs. 10, 11) is the result of the energy balance between powder melting and heat loss into the substrate (or a previously fabricated layer). For small powder layer thickness, important fraction of laser energy is spent on a substrate melting. Keeping in mind particle size distribution (< 20 µm), one may note that it is difficult to guarantee the uniform powder layer thickness in the range 10-20 µm. Most probably the results of temperature measurements are influenced by this fact.

It is known that the coefficient of thermal conductivity of a powder bed is 20 times lower than that of bulk material [12]. That is why the mean temperature grows with the powder bed thickness. Starting from a certain critical value the pyrometer signal and brightness temperature reaches the maximum and stable value because the contact between melted powder layer and the substrate is lost, and, thus, all the laser energy is absorbed by powder, and there are no heat losses into the substrate (fig. 10).

5.5 Monitoring during parts manufacturing: Influence of manufacturing strategy

Three different parallelepipeds (10x10x3 mm³) were fabricated by applying three different manufacturing strategies, totally 57 powder layers were melted.

The first strategy was the so-called “one-zone” technique (fig. 12 b1,b2). Each powder layer is processed by unidirectional laser beam passes with 120 µm hatch distance that is equal to the track width. The laser beam acts only on the currently processed powder layer without affecting the previously fabricated tracks. Objects thus fabri-
cated show vertical column-like structure. Regular vertical oriented zones with high porosity are easily seen.

The second strategy is the so-called “two-zone” technique (fig. 13b1, b2).

Each powder layer is processed in two steps: (1) first, the powder layer is processed with a hatch distance equal the average width of the vector which is about 120 µm for the applied powders and process parameters; (2) the laser beam passes in between the melted tracks of the same layer thus remelting no powder but two neighboring tracks previously fabricated (fig. 13b2). By this strategy, similar column-like structures are produced but with less porosity.

The sample surface is more homogeneous. Evident decrease of the pyrometer signal (fig. 13a) when the laser beam remelts the tracks without powder is observed.

![Figure 13](image)

**Figure 13.** (a) - Evolution of the pyrometer signal for the 57th layer fabrication using the two-zone strategy; (b) - photos of the fabricated object: the 57th layer top views (b1) and cross-section (b2). Process parameters: scanning velocity $v = 120$ mm/s, incident laser power $P = 32$ W; hatch distance $\delta = 120$ µm; 50 µm powder layer thickness.

The third applied strategy is also “one-zone” technique (fig. 14b1,b2): each powder layer is processed by one pass but with 60 µm hatch distance. In this case, the laser beam melts simultaneously the previous track as well as the powder layer. The level of the pyrometer signal is lower than in fig. 12 because of the energy losses onto the previous tracks remelting.

![Figure 14](image)

**Figure 14.** (a) - Evolution of the pyrometer signal for the 57th layer fabrication using one-zone strategy; (b) - photos of the fabricated object: the 57th layer top views (b1) and cross-section (b2). Process parameters: scanning velocity $v = 120$ mm/s, incident laser power $P = 32$ W; hatch distance $\delta = 60$ µm; 50 µm powder layer thickness.

6. Conclusions

The original optical diagnostic system was developed and integrated with commercial PHENIX PM-100 machine. It was found that the pyrometer signal from the laser impact zone and 2D temperature mapping from HAZ are rather sensible for variation of the main operational parameters (powder layer thickness, shift between consecutive laser beam passes, scanning velocity, etc.), and could be used for on-line control of manufacturing quality.

Variations of the pyrometer signal and brightness temperature with operational parameters were analyzed for the following cases:

- **Variation of the hatch distance for 50 µm thickness powder layer (good metallurgical contact with substrate):** Generally, the pyrometer signal increases with hatch distance. Three different zones of signal variation are found: (a) constant signal for low hatch distances ($\delta < 105$ µm) when the consecutive track is so close to the previous one that they form direct metallurgical contact; (b) constant signal for large hatch distances ($\delta > 120$ µm) when the interaction between the tracks is practically absent, and the volume of remelted powder per single track reaches maximum value; (c) transition zone ($105$ µm $< \delta < 120$ µm) where the pyrometer signal increases with hatch distance.

- **Variation of the hatch distance for 1 mm thickness powder layer (no metallurgical contact with substrate):** Generally, the pyrometer signal decreases with hatch distance. For the hatch distance less than 300 µm, a significant increase of the pyrometer signal at the beginning of the scanning is caused by heat accumulation in the previously fabricated tracks which are in direct metallurgical contact, and by low heat losses into the surrounding powder layer.
Variation of the powder layer thickness: The increase of the pyrometer signal and the maximum brightness temperature in the HAZ with powder layer thickness from 20 µm up to 120 µm is the result of the energy balance between powder melting and heat losses into the substrate. Starting from a certain critical value, the pyrometer signal reaches the maximum and stable value because the contact between a melted powder layer and a substrate is lost, and thus, all the laser energy is absorbed by powder, and no heat losses into the substrate takes place.

Different melting conditions in the “one-zone” and “two-zone” techniques result in different thermal cycles of powder consolidation, different solidification conditions, resulting structure and porosity. The pyrometer signals differ as well, in particular, for the “two-zone” technique.

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References

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