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Influence of the opto-mechanical chain on the energy provided by the laser spot to the material in laser powder bed fusion processes.

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Abstract

The additive manufacturing machines used in laser powder bed fusion processes are composed of an opto-mechanical chain whose purpose is to focus the laser in the work plane to locally fuse the material with the required energy. The opto-mechanical chain does not only position the laser spot, it also induces a modification of its shape and thus the distribution of energy brought to the material. As a result, the shape of the laser spot is not the same at every point on the machine, which can have an influence on the characteristics of the produced parts. This aspect related to opto-mechanical chain technology is very often ignored, particularly in thermal modelling. In this work, we study the impact of opto-mechanical chains composed of post-objective focusing systems on the energy distribution of the laser spot in the entire achievable space by the system. For this purpose, mathematical models are used to evaluate the position of the laser spot in the work plane as well as the orientation of the laser beam. An energy model of Gaussian laser beams is then used and applied to these geometric models. The coupling of these two models makes it possible to study the energy distribution of the laser spot at any point in the workspace of an additive manufacturing machine. The work is confirmed with experimental measurements made on a test bench representative of an industrial additive manufacturing machine.

Optical, Laser, Model, Laser beam machining (LBM)

1. Introduction

In additive manufacturing by Laser Powder Bed Fusion (LPBF), knowledge of the size of the laser spot and the melting pool are important elements, as they condition many parameters during the trajectory generation process. Thus, this work focuses on the influence of the opto-mechanical chain on the distribution of energy supplied to the material.

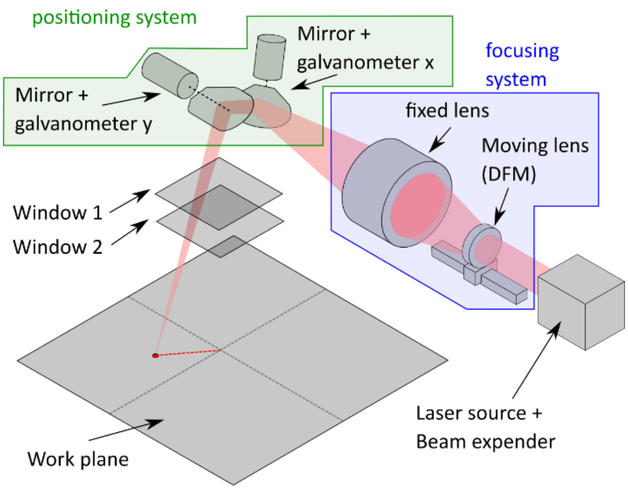

Figure 1. Opto-mechanical chain of an additive manufacturing machine by laser powder bed fusion. Post-objective focusing system.

These opto-mechanical chains consist of two main blocks identified in figure 1: the focusing system and the positioning system. In LPBF additive manufacturing, whatever the machines, the positioning system is always the same. These are two movable mirrors that allow the orientation of the outgoing laser beam to be controlled. On the other hand, to focus the laser beam in the work plane, two main types of technological solutions are distinguished. Ehrmann [1] describes these two types of focusing systems called pre-objective and post-objective. Pre-objective systems consist of a fixed lens located after the positioning system that focuses the laser beam in a focal plane. The post-lens systems shown in figure 1 consist of a movable lens and a fixed lens. The combination of these two lenses allows to control the focusing distance and therefore at any time to focus the laser beam in the work plane.

Previous work has been done to qualify the shape of the laser spot and its distribution. Deshmukh et al. [2] presents measurements made on three different types of focusing systems. However, the work on the post-objective system is not well documented. In order to standardize the shape of the laser spot and its energy distribution over the entire working area, the development carried out in [3] consists in proposing a new hybrid opto-mechanical chain. This one is qualified, but is not compared to standard opto-mechanical chains. It is also possible to find purely geometric approaches [4] based on the deformation of a pixel by the opto-mechanical chain. However, not all these approaches directly and mathematically address the influence of the opto-mechanical chain.

The work carried out in this article concerns more specifically the qualification of the energy deposited on the work plane in opto-mechanical chains composed of post-objective focusing systems. The numerical values presented are typical values used in additive manufacturing machines.

The article is organized as follows: section 2 describes the assumptions and parameters used in mathematical models. Section 3 presents the two phenomena that influence the energy supplied to the material: the increase of the spot size as a function of the focal length and the incidence angle of the laser beam with respect to the work plane. Experimental measurements are carried out in section 4 which confirm the theoretical results. Finally, a conclusion on the study is provided in section 5 in order to highlight some important points.

2. Assumptions and parameters

In order to characterize the geometry and the intensity profile of the laser spot in the work plane, wave optics hypotheses are used. The assumptions and parameters are defined in the following list and are presented in figure 2.

1. The laser beam is considered as Gaussian beam;
2. The laser beam wavelength is noted λ_l and is equal to $1.06\ \mu m$;
3. The laser beam diameter at the entrance of the equivalent lens of the focusing system is noted d_l and is equal to $20\ mm$;
4. The focal point is named $\boldsymbol{P_f}$;
5. The laser beam radius is called w. This radius is minimal at the focus point $\boldsymbol{P_f}$ and is named "waist" with $w(z' = 0) = w_0$;
6. The defocusing parameter is noted h_f and corresponds to the height of the focal point with respect to the work plane;
7. The focusing distance D_f depends on the position of the laser spot in the work plane and the defocusing height.

The laser beam radius $w(z')$ as no immediate meaning, it is an energy threshold. This distance corresponds to the value from which the intensity of the laser spot is equal to $1/e^2$ times the maximum intensity $I(z')$ of the laser spot (with $e = \exp(1)$). This criterion is often used to characterize the diameter of a laser beam.

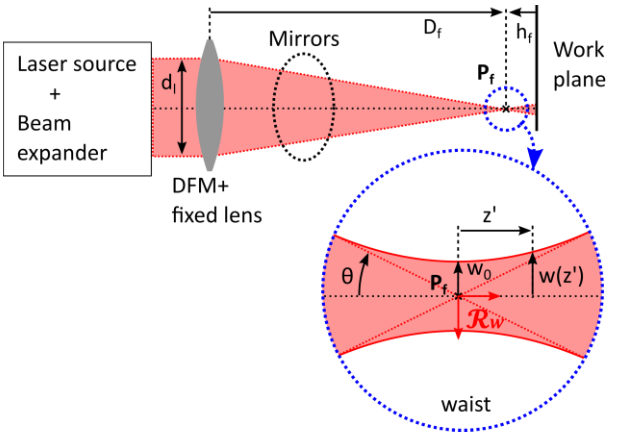

Figure 2. Parameterization and representation of the waist.

Opto-mechanical chains composed of post-objective focusing systems allow the laser beam to be focused in space and not only in the work plane. Thus the notion of defocusing in relation to the work plane is introduced with the parameter h_f, this adjustable parameter therefore allows to modify the laser spot size and consequently the energy distribution in the work plane by acting on the focusing of the beam.

Before going into details, it is also necessary to understand that the reflection of the laser beam on the mirrors has no impact on the shape of the laser spot. Indeed, this reflection does not change the distance travelled by each light beam.

3. Modification of the shape and the distribution of energy

3.1. Influence of focal length

The first parameter influencing the laser spot geometry and in particular the waist size w_0 is the focusing distance D_f. The laws of optics allow to establish equation (1) with θ the angle of divergence of the laser beam:

$$\theta = \frac{\lambda_l}{\pi \cdot w_0} \tag{1}$$

Using figure 2, it is possible to define θ as a function of the focusing distance using the triangle formed by the lens and the waist (cf. equation (2)).

$$\theta = \arctan\left(\frac{d_l}{2 \cdot D_f}\right) \tag{2}$$

The combination of equations (1) and (2) allows to express the waist as a function of the focal length. This relationship is written in equation (3).

$$w_0 = \frac{\lambda_l}{\pi \cdot \arctan\left(\frac{d_l}{2 \cdot D_f}\right)} \tag{3}$$

The study of this function shows that an increase of the focusing distance leads to an increase of the waist. If we consider only the variation of the laser spot radius due to the focusing distance then it is possible to obtain figure 3, which shows the evolution of the laser spot size over the entire area accessible by the opto-mechanical chain (full field). The calculation of the focusing distance D_f as a function of the position of the laser spot in the working plane (x, y) is performed using the geometric models described in article [5]. Thus for the full field the waist size increases by nearly 10 % between points $\boldsymbol{P1}$ $(0,0)\ mm$ and $\boldsymbol{P2}$ $(330,\ 291)\ mm$. The point $\boldsymbol{P3}$ $(260,\ 260)\ mm$ is used in the rest of the paper to perform measurements.

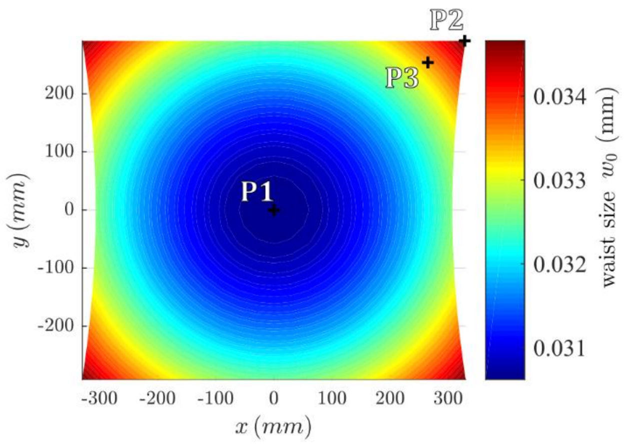

Figure 3. Variation of the waist size in the work plane.

3.2. Influence of laser beam orientation

Once the influence of the focal length is quantified, it remains to define the influence of the laser beam orientation on the laser spot.

First, to simulate the real shape of the laser spot, it is necessary to start from the Gaussian equation that modelsthe whole laser beam. For a Gaussian laser beam, the intensity of a point $\boldsymbol{M}$ of coordinates (x', y', z') in the waist coordinate system $\mathcal{R}_w$ is expressed by equations (4), (5) and (6).

$$w(z') = w_0 \cdot \sqrt{1 + \left(\frac{\lambda_l \cdot z'}{\pi \cdot w_0}\right)^2} \quad (4)$$

$$I(z') = I_0 \cdot \left(\frac{w_0}{w(z')}\right)^2 \quad (5)$$

$$I(x', y', z') = I(z') \cdot \exp\left(-2 \cdot \left(\frac{x'^2 + y'^2}{w(z')}\right)\right) \quad (6)$$

To obtain the laser beam intensity in the work plane, it is necessary to establish the transfer matrix from the waist coordinate system $\mathcal{R}_w$ to the coordinate system linked to the point $\boldsymbol{P}$ located in the work plane $\mathcal{R}_p$ (cf. figure 4). This transfer matrix is determined by using $\overrightarrow{u_6}$ the orientation of the laser beam relative to the work plane, and $\boldsymbol{P} = (x, y)$ the position of the laser beam relative to the work plane. These two elements are obtained using the geometric models described in [5].

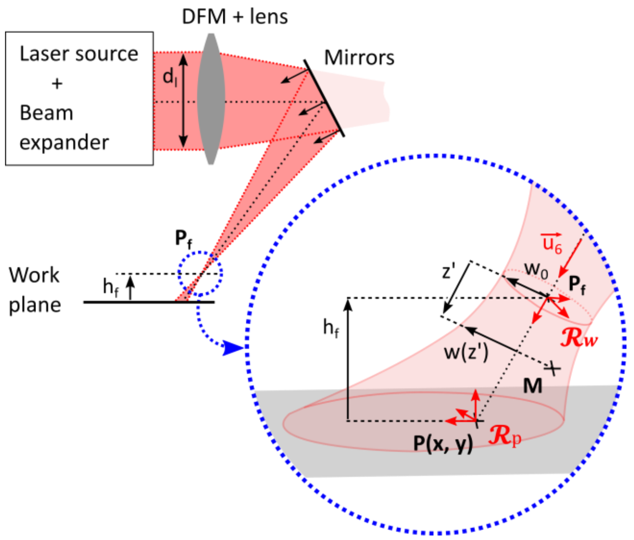

Figure 4. Intersection between the Gaussian laser beam and the work plane.

Once the transfer matrix has been established, the position of any point $\boldsymbol{M}$ is expressed in $\mathcal{R}_p$. The coordinates of $\boldsymbol{M}$ in this coordinate system are named x_1, y_1 and z_1. This allows the intensity field of the laser beam to be calculated in $\mathcal{R}_p$, i. e. $I(x_1, y_1, z_1)$. To evaluate the intensity of the laser beam in the work plane, it is therefore sufficient to set $z_1 = 0$.

Figure 5 shows several intensity distribution results in the work plane. All these results are expressed with the same normalized intensity scale. This scale is established in relation to the maximum intensity of the laser beam which is located in the upper left case. Each column presents the laser spot shape at a specific position in the work plane. This shows that at the center of the work surface the laser spot shape is circular, while elsewhere the spot is elliptical. The direction of the ellipse depends on the orientation of the incident beam and therefore on the position of the point in the work plane. The first row shows the results when the dependence of the waist size w_0 on the focal length D_f is not considered. The second raw shows the case where the defocusing parameter is set to $2\,mm$. Defocusing leads to a significant increase in spot size and a decrease in the peak intensity at the center (Gaussian circular or elliptical). The last row includes the variation of the waist size according to the focal length presented above. This corresponds to substituting in equations (4) and (5) the value of w_0 defined by equation (3).

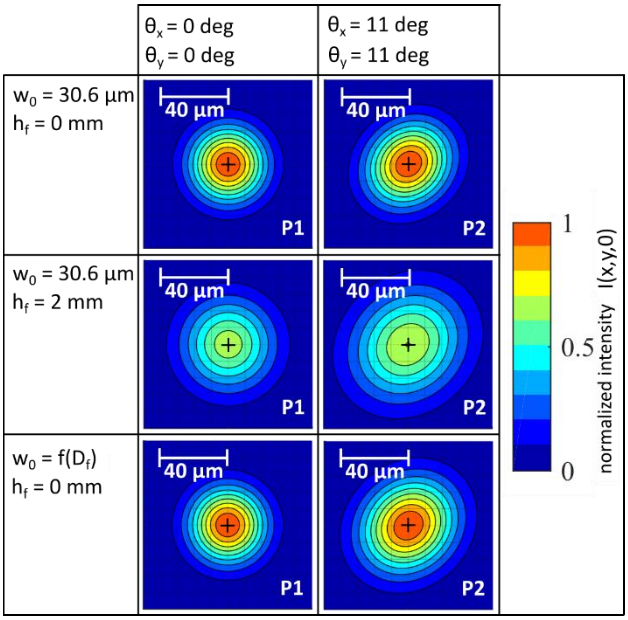

Figure 5. Energy distribution of the laser spot. The columns correspond to two positions of the laser spot P1 and P2. The rows correspond to three configurations (size of the laser spot fixed or depending on the focusing distance and defocusing equal to 0 or 2 mm).

The maximum variation in the laser spot shape corresponds to the difference between the laser spot at the center of the work plane and at one extremity. Taking into account the two aspects previously shown, a laser spot with a radius of $30.6\,\mu m$ is transformed into an ellipse with a semi-major axis of $40\,\mu m$ and a semi-minor axis of $34\,\mu m$. The change in shape is therefore quite significant when using the full field. The impact in the manufactured area is slightly less important, as the printing area is most of the time a restriction of the reachable space.

4. Experimental validation of the energy profile

In order to experimentally verify the previous simulation results, a test bench representative of an industrial manufacturing machine is used. This test bench is instrumented with a CCD matrix positioned in the work plane to visualize the laser spot trace. To avoid saturation of the measurement, optical filters are used, moreover the exposure time is also adjusted. For safety reasons and in order to be able to carry out a measurement, the laser beam used at the input of the opto-mechanical chain is at a very low power ($1\,mW$).

Due to the small size of the focused laser spot ($\approx 70\,\mu m$), the pixel size of the CCD matrix ($5.3\,\mu m$) and the small spatial variation of the energy distribution to be measured, the measurement of the deposited energy is performed with a low spatial resolution. Finally, the experimental measurement is also limited by the incidence angle of the laser beam. Due to the size of the camera and optical filters, it is not possible to measure the energy deposited at point $\boldsymbol{P2}$ because the orientation of the incident laser beam is too important and the laser spot exits the CCD matrix. Thus the measurement is carried out at a point $\boldsymbol{P3}$ previously presented.

Figure 6 shows the experimental results from the laser spot measurement. The first row of the table shows that the laser beam used is not quite Gaussian, there is a slight deformation. The comparison of row 1 and row 2 of the table shows the influence of defocusing on the shape of the laser spot. The experimental results are not as obvious as the theoretical results, but they confirm the increase in diameter and the decrease in the maximum intensity of the laser spot. For larger defocusing, this effect is more pronounced. Finally, the measurement presented in the third row clearly shows the deformation of the laser beam and the increase in diameter. However, the energy intensity of this third measurement cannot be directly compared to previous measurements. Indeed, given the angle of incidence of the laser beam, it travels a greater distance in the optical filter and is therefore more attenuated. This third measure is therefore normalized separately.

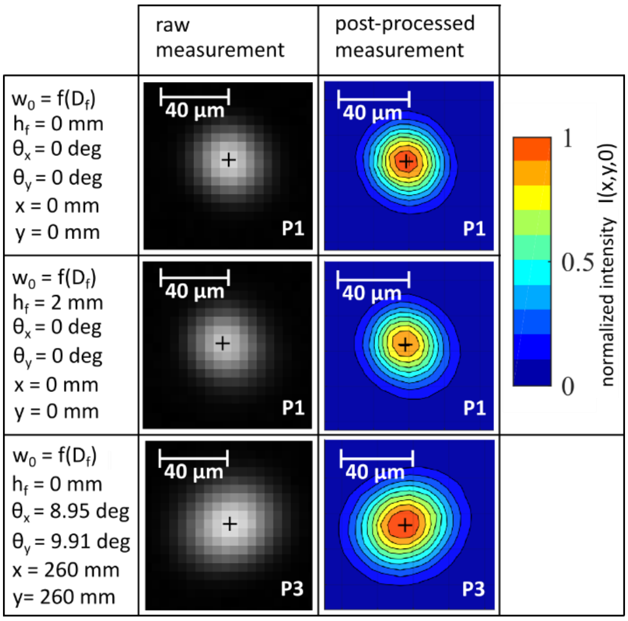

Figure 6. Experimental energy distribution of the laser spot. The three rows represent three different configurations. The left and right columns respectively represent the raw measurement and the post-processed measurement results.

5. Conclusion and perspectives

In opto-mechanical chains with post-lens focusing systems, the laser spot shape and the energy distribution are influenced by two elements. On one side the focusing distance which is variable in order for the waist to belong to the work plane and on the other side the orientation of the incident laser beam on the work plane which generates an elliptical shaped laser spot. These two aspects lead to significant deformations of the laser spot, particularly on the ends of the laser accessible areas.

In most machines currently in use, the effective printing area is a significant restriction of the laser spot accessible area. This aspect allows, among other things, to contain the deformations of the laser spot and the variations in energy distribution. However, for more productivity and to be able to manufacture larger parts, the build platform size must be larger, so manufacturers are looking to use the full area covered by the galvanometric heads as much as possible. In this perspective, it becomes necessary to know the energy distribution of the laser spot to consider it and finely control the process.

The work performed can also be applied to the measurement of the deposited energy during a trajectory and no longer only in static way. This would make it possible to quantify the influence of energy distribution on a complete trajectory and show the impact of the position of the part in the work plane. In dynamics, however, the energy interpretations are more complex due to the influence of the dynamics of the actuators and the numerical control on the realized trajectories. The model presented can also be an additional brick for the nesting of the part on the build platform before starting the manufacturing process.

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