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Non-linear thermal model of the Direct Laser Melting Process considering the adhesion of the consolidated material to the substrate using a domain with discontinuous material properties

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Abstract

In the Direct Laser Melting Process the distribution of the heat between the powder flow and the substrate plays a crucial role in the adhesion of the supplied material. Nevertheless, during the interaction between them, laser beam and powder flow with a given section, the growth of the consolidated material introduces a continuous change in the conditions of the process which makes it difficult to evaluate the effective amount of energy addressed to the substrate leading to an effective melting of it. The present study proposes a non-linear thermal model where the thermo-physical properties of the domain change dynamically according to the evolution of the geometry of the supplied material, as a function, in turn, of the powder flow and the process speed. Important aspects such as the influence of the process parameters, especially, the shielding associated to the powder flow, are evaluated as conditioning factors for a successful adhesion.

Keywords: DLM; Adhesion-to-the-substrate; Powder-consolidation; energy-absorption

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1. Introduction

Adhesion between consecutive layers is indispensable to build a sample by means of additive manufacturing. To make it happen, the substrate or the previous consolidated layer has to experience melting from its surface to several micrometers below it in order to weld with the melt pool formed with the supplied powder when it is heated with the laser source.

A lot of effort has been employed in the study of additive manufacturing processes where the adhesion is considered in an explicit or an implicit way, like in Cordovilla, 2018. From the experimental point of view, parametric studies have been carried out to determine combinations of process parameters leading to a satisfactory result, for both DLM and SLM. Numerical studies can be classified in two groups; thermal approach exclusively, like Kruth, 2007, or thermo-fluidic approach as in the case of Khairallah, 2014. In both cases adhesion is presented as the result of the conditions of the process, in an aggregated way, without further analyzing how the energy reaches the substrate making it melt.

The thermal energy that reaches the substrate can be considered as the combination of several contributions of different nature:

a) The heat coming from the melt pool formed from the powders: The powder can be considered as a media where the heat is accumulated due to its very low thermal conductivity associated to the limited contact surface among particles. Once it becomes liquid, the contact area increases and the heat from the melt pool is quickly transferred to either, the substrate or the particles not initially reached by the laser around the melt pool

b) The latent heat from the solidification of the melt pool formed from the powders.

c) The laser radiation which is neither absorbed nor reflected by the powder, being capable of reaching the substrate.

The present study aims at analyzing the influence of the different mechanisms which contribute to the heating of the substrate, quantifying the contribution of each of them independently. This knowledge allows not only for designing the process by adjusting the parameters in order to get a specific degree of dilution between consecutive layers, but also, for understanding the physics basis of the adhesion phenomenon and its implications in consolidation.

The nature of adhesion is the same for the technologies currently most wide spread SLM and DLM; experimental tracks can be seen in Yadroitsev, 2010. Nevertheless, while in SLM the powder is allocated on the substrate before the irradiation, in DLM a constant injection of power takes place simultaneously to the laser irradiation, leading to a continuous change of the conditions in which the substrate is exposed to the energy supplied by the laser. In order to deal with this circumstances, a numerical thermal model is proposed where the properties of the domain dynamically change to reflect the effect of the heated powder constantly interposing between the laser source and the substrate. The properties of this tunable domain evolve, in consequence, from representing a media where the laser reaches the substrate directly, to be a prescribed amount of molten powder deposited on the substrate, transferring its heat to it, and, simultaneously growing and receiving the heat from the laser source.

2. Experimental motivation

AISI 316L was used as working material for the powder and substrate, due its good characterization in the case of DLD applications such as Cuo, 2017, or, Yadollahi, 2015. The substrate consisted of 1 cm thick plates. An IPG fiber laser with 6 kW of maximum output power releasing radiation at 900 nm was the laser source, focused on a diameter of 4.58 mm. Following a DLM scheme, single ribbons were consolidated on the substrate varying the conditions of mass flow, laser power and process speed. All the samples were cut, conveniently ground and polished, and analyzed by optical microscope.

The influence on the degree of melting in the substrate associated to three representative process parameters; laser power, *P*, process speed, *V*, and the powder mass flow, *m*, is analyzed. Examining the experimental result of varying each of them individually, keeping the others fixed will allow for noticing its respective influence on the degree of fusion in the substrate. This empirical work, as a preliminary step to the definition of the numerical model, aims at identifying qualitatively the phenomena that the model needs to describe and quantify.

2.1. Influence of the mass flow

Two sets of experiments were carried out to analyze the response of the substrate when varying the mass flow from 9.3 g/m to 18.6 g/min for a prescribed laser power of 2000 W, considering conditions of relatively low process speed of 400 mm/min and of relatively high process speed of 800 mm/min. Table 1 synthetizes the process parameters.

Table 1. Process parameters to study the influence of the mass flow

Test number	*P* (W)	*V* (mm/min)	*M (g/s)*
1	2000	400	9.3
2	2000	400	12.4
3	2000	400	18.6
4	2000	800	9.3
5	2000	800	12.4
6	2000	800	18.6

Figure 1 shows the cross section of the tests indicated in Table 1. The values of the depth of melting under the substrate at the center of the track have been highlighted because they will be taken as reference.

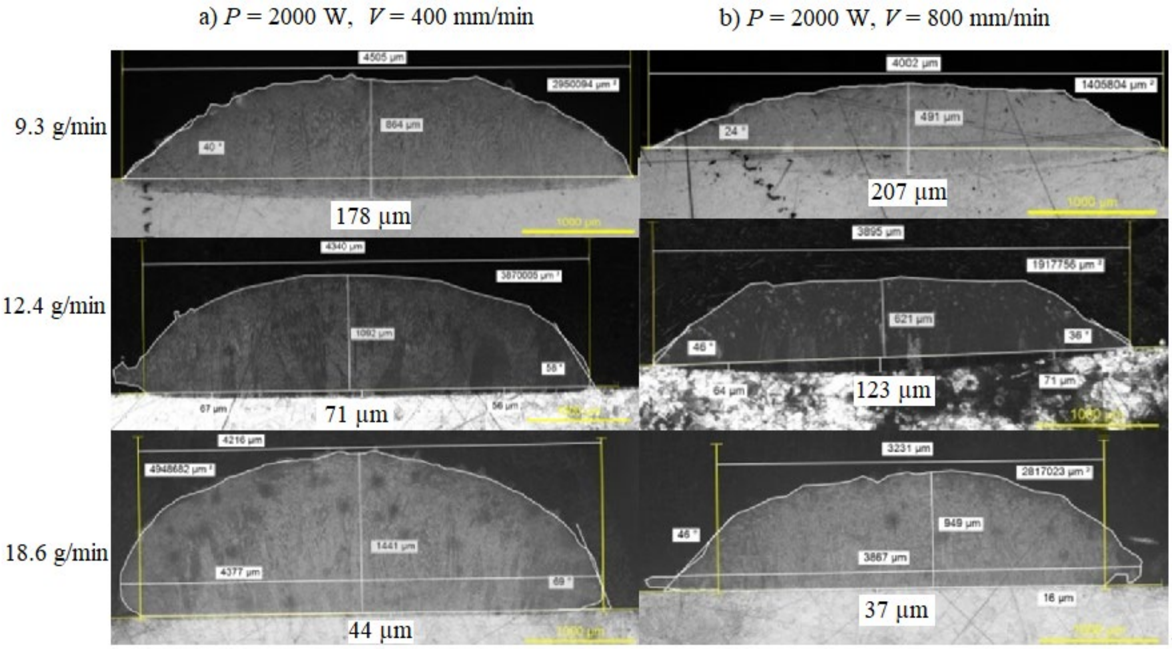

Fig. 1. (a) Tests with relatively low process speed; (b) tests with relatively high process speed

The results in Figure 1 show that the increase of the mass flow results in a limitation of the energy available to melt the substrate.

In Figure 2 the tendency of the depth at the center of the track is displayed as a function of the mass flow.

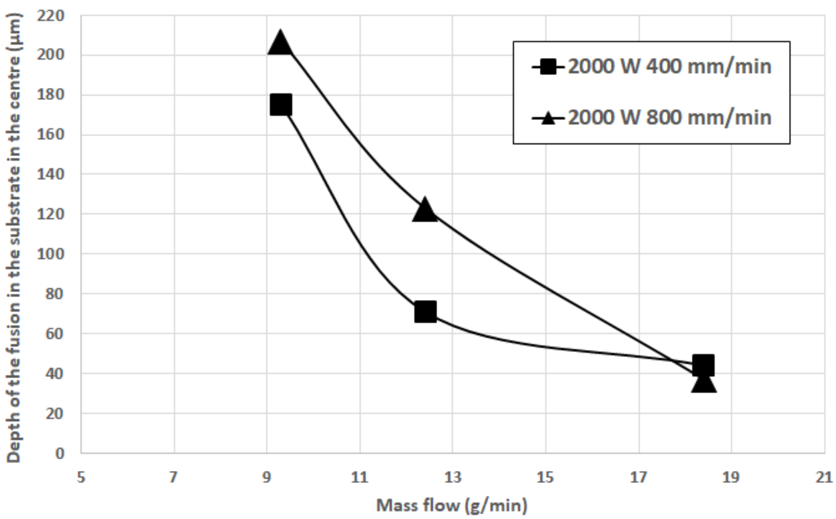

Fig. 2. Evolution of the fusion depth at the substrate as a function of the mass flow

From the results in Figures 1 and 2 it can be induced that the mass flow of powder is an obstacle between the energy supplied by the laser beam and the substrate. This idea is reinforced by the fact that tests with a higher process speed achieve larger levels of fusion in the substrate than the slower processes. In a DLM configuration, the interaction time (beam diameter divided by the process speed) affects both, the energy and the powder supplied on a given point. In the step from 400 mm/min to 800 mm/min, both magnitudes, energy and powder supplied on a given point, are divided by two; nonetheless, the melting of the substrate is greater in the faster processes, it can only be due to the smaller amount of powder accumulated on each point as a consequence of the shorter interaction time. From this point of view, the modeling of the mass flow can be configured as a medium where a significant part of the energy is absorbed, not reaching the substrate directly, and whose cumulated heat is not enough by itself to produce the melting of the substrate.

2.2. Influence of the laser power

Four levels of laser power of 2000 W, 2400 W, 2600 W and 2800 W are used with a mass flow of 18.6 g/min and a process speed of 600 mm/min in all the cases. Figure 3 show the cross section of each of the four tests. Once again, the capability of the mass flow to prevent the energy from reaching the substrate is highlighted. In the cases of the tests with the lower levels of power, of 2000 W and 2400 W, the energy from the laser source is not capable of traversing the barrier of the mass flow, thus not causing a significant level of melting under the substrate. Nevertheless, in the transition from the test with 2400 W to the test with 2600 W the depth of fusion under the substrate grows from a value of around 40 µm to a value of about 140 µm. Quantitatively, an increment of the laser power by a factor of around 1.08 resulted in a larger fusion of the substrate by a factor of around 3.5. When the laser power continues to be increased from 2600 W to 2800 W, the depth of the fusion in the substrate is observed to keep experiencing growing in a factor larger than the factor in which the power has been increased.

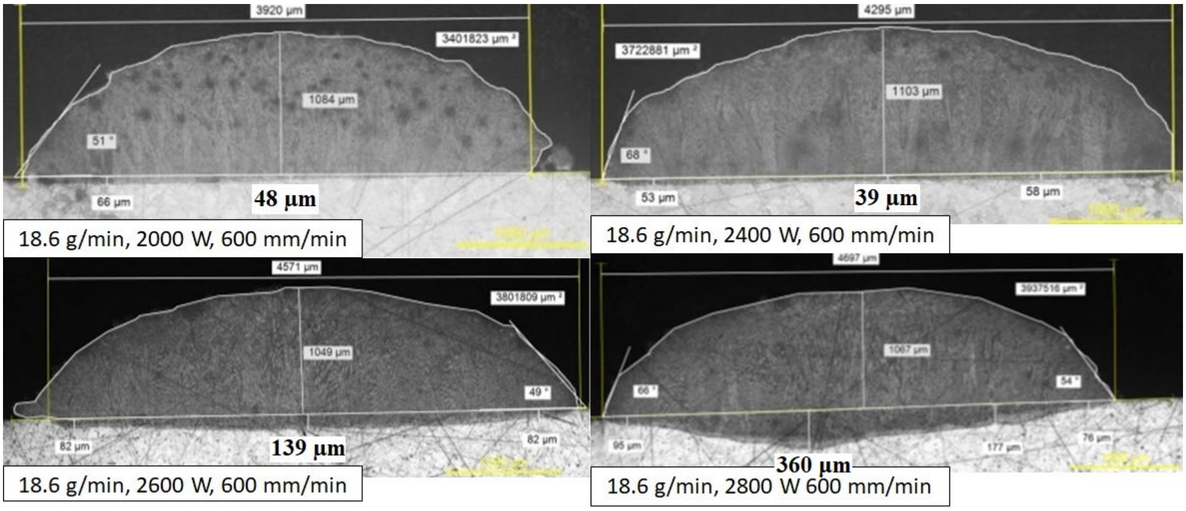

Fig. 3. Evolution of the fusion depth at the substrate as a function of the laser power

2.3. Influence of the process speed

To evaluate the influence of the process speed on the fusion of the substrate, three tests have been carried out with process speeds of 400 mm/min, 600 mm/min and 800 mm/min and fixed values of power of 2600 W and mass flow of 18.6 g/min. Figure 4 shows the cross section corresponding to the three tests.

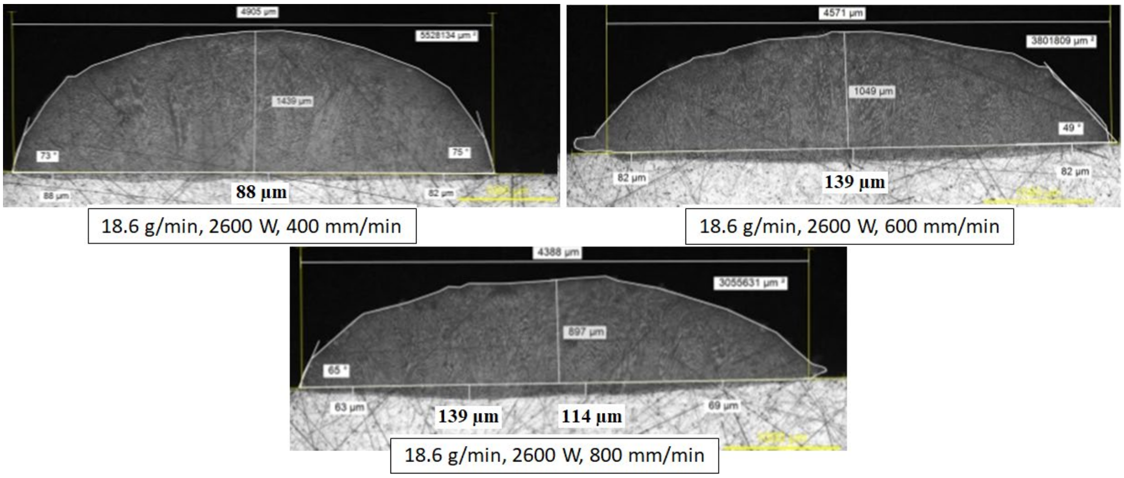

Fig. 4. Evolution of the fusion depth at the substrate as a function of the process speed

As indicated in section 2.2, the process speed determines the time during which a point is receiving energy from the laser source as much as the time for the powder to be accumulated on the same point. In the increment from 400 mm/min to 600 mm/min, the effect of a shorter accumulation of powder on the substrate predominates over the reduction of the time available to supply energy, as the higher depth of melting indicates. For an even higher process speed, the interaction time reduces significantly, and, although the reduction of the shielding effect associated to the shorter amount of accumulated powder, the energy supply is not enough to further extend the depth in which melting is happening in the substrate.

3. Thermal model of the continuously growing accumulated material on the substrate

Experiments in section 2 show that the powder mass flow limits the capability of the substrate to experience melting: the powder mass flow absorbs a significant amount of the electromagnetic energy from the laser beam. When the amount of powder in relation with the laser power is large enough, there is not enough energy on the substrate to melt it, despite receiving, as a secondary heat source, the heat from the melt pool of the powder mass flow. Considering the phenomena observed, the definition of the model can be made following a particular sequence: The calculation of the absorption of the energy from the laser by the powder flow as a function of its magnitude has to be followed by the calculation of the space-time evolution of temperature in the powder flow considering its absorption. Then, the heating of the substrate with the energy that traverses the powder mass flow considering the continuously changing conditions for the heat transfer due to the growing of consolidated material on the substrate is obtained, in conjunction with the secondary heating of the substrate as a consequence of the contact of the heated powder flow.

3.1. Absorption coefficient of the powder mass flow.

The powder mass flow is considered as an isolated media until it touches the surface of the substrate, when it is assumed to be already in liquid state. While the powder flow keeps isolated, the laser energy transferred to it is integrally employed in increasing its temperature, and conduction of the heat does not happen beyond the scale of the powder particles. In these conditions the minimum level of power, P, which is needed to reach the melting point of the material, T_m, from the initial temperature, T_0, as a function of the mass flow, m , is given by equation (1), where C_p represents the heat capability of the material:

$$P_{min} = mC_p(T_0 - T_m). \quad (1)$$

The power obtained by equation (1) has to be concentrated within the area of the laser beam leading to the so called power density or irradiance, I. The minimum level of irradiance which gives place to melting of the powder flow is obtained considering that laser power is uniformly spread along the cross area of the beam, as equation (2) indicates.

$$I_{min} = P_{min}/(\pi r_{beam}^2). \quad (2)$$

From the experimental point of view, the maximum width, r_{max}, of the final consolidated powder indicates the region along which the real laser beam with Gaussian density distribution, denoted as $I_G(r)$ in polar coordinates (r is the distance to the center of the beam), has surpassed the value of I_{min} divided by the absorption coefficient, A, which is the magnitude to be determined

The absorption can be calculated, therefore, as the minimum irradiance which is capable of causing the melting of the substrate, divided by the irradiance of the real Gaussian beam at the furthest position from the center in which the powder was consolidated, as equation (3) synthetizes

$$A = I_{min}/I_G(r_{max}) \quad (3)$$

3.2. Calculation of temperature in the powder flow.

The laser beam interacts with the powder mass flow before it reaches the substrate. It consists of a low-density conglomerate of quasi-isolated particles. A Finite Element Model has been used to determine the temperature of the mass flow when reaching the surface of the substrate. It is modeled as a continuous domain whose density is the density of the suspension of particles in the volumetric flow, τ, of the drag gas which moves the powder particles. In this way, the apparent density, ρ_{ap}, of the particles when they are dragged by the inert gas is given by equation (4),

$$\rho_{ap} = m/\tau \quad (4)$$

The heating time of the powder flow is assumed to correspond to the time during which particles are flying from the nozzle to the top of the substrate. The speed of the particles in their flight from the nozzle to the substrate, V_f, can be calculated as the result of the volumetric flow of the drag gas through the output section of the nozzle, S_n. The distance to be travelled by particles varies from the initial separation between the nozzle and the substrate, h_0, and the separation between the consolidated ribbon and the nozzle, h_f. In a first approach, for the sake of simplicity, the mean distance corresponding to both situations will be taken as the reference distance for the calculation of the heating time, t_h, as equation (5) indicates.

$$t_h = (\tau S_n)/[(h_0 - h_f)/2V_f]. \quad (5)$$

Temperature calculated by means of applying the properties obtained in equations (4) and (5) will be projected on the growing front of the consolidated material from the initial instant when nothing is on the substrate to the final instant of the interaction of the laser beam with a given section where a ribbon of consolidated material is built. This scheme can be followed in Figure 5

Figure 5 shows the evolution of the amount of the consolidated material on the substrate on a given section. This growing of material is used as a change of the properties of the domain above the substrate, from being air, allowing the laser energy to reach the substrate directly, to be consolidated material.

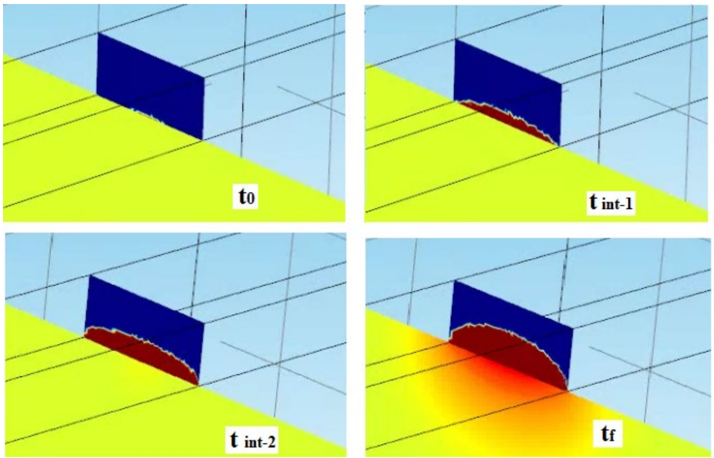

Fig. 5. Growth of the consolidated material (red) on the substrate (yellow), to identify the evolution of the properties on the domain and the surface on which the temperature of the powder flow is going to be projected. The blue domain represents air

4. Results

4.1. Temperature evolution in the substrate from the heat of the melt pool and from the laser source

The space-time evolution of temperature in the substrate is finally obtained as the result of the indicated factors: the heat from the melt pool formed with the interaction of the laser and the powder flow, the laser radiation reaching directly the substrate, at the initial instant, and then, reaching the top of the consolidated material in process of growing.

The experimental test with a laser power, P = 2000 W, a powder mass flow of m = 18.1 g/min, and a process speed, v = 400 mm/min is studied by means of the numerical model.

Figure 6 depicts the evolution of temperature at the top of the consolidated material and under the substrate. The top of the consolidated material is a point whose height is constantly being increased during the interaction of the powder flow with a given section; it constantly receives the laser radiation that is capable of traversing the powder flow. In the case of the substrate, a clear discontinuity is observed in the temperature evolution of the monitored points. This discontinuity is associated to the abrupt change in the heat transfer conditions experienced by the substrate from when a certain amount of consolidated material is allocated on it. From this moment, the heating rate of the substrate decelerates.

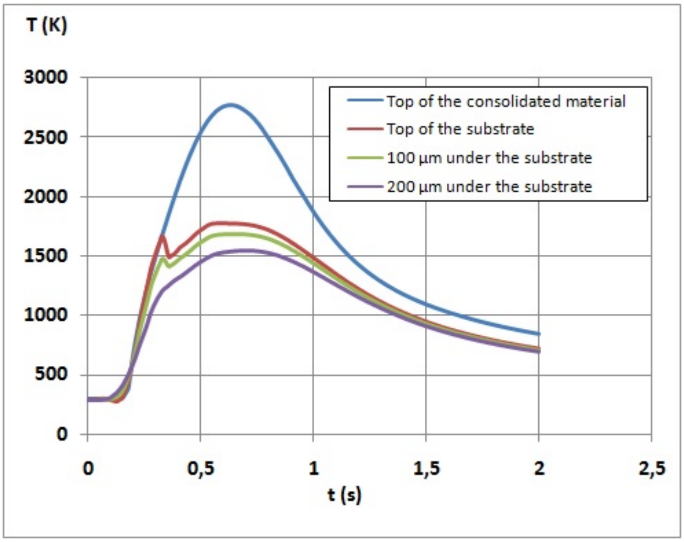

Fig. 6. Temperature on the top of the consolidated material (blue line) and under the substrate in the central point of a given section

The temperature evolution in Figure 6 supports the experimental result shown in Figure 1 at the bottom to the left. The melting temperature of the working material (around 1700 K) is barely surpassed in the local vicinity of the top of the substrate, in correspondence with the 44 µm along which melting took place under the substrate in the experimental test.

5. Conclusions

The thermal modeling considering a domain with thermal properties changing in accordance with the growing of the consolidated material has been presented as a powerful tool to predict the conditions leading to a good adhesion between the molten material and the substrate. Crucial aspects of the presented approach are the spread of the energy between the mass flow and the substrate. A specific methodology to obtain the absorption coefficient of the mass flow has been proposed.

By means of the proposed methodology the process parameters can be adjusted with numerical simulation to design a process with a prescribed degree of consolidation between consecutive tracks. The geometry of either, the substrate or the previously consolidated track has to be specifically considered in order to reproduce proper heat transfer conditions.

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