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Finite element modeling of melt pool dynamics in laser powder bed fusion of 316L stainless steel

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Abstract

In Laser Powder Bed Fusion (LPBF), melt pool dynamics stability determines the overall quality of a manufactured component. In this work, a numerical model of the LPBF process was developed in order to study and fully understand the behavior of the melt pool dynamics. The numerical model takes into account most of the manufacturing parameters, thermophysical properties, an enhanced thermal conductivity approach and a volumetric heat source in order to precisely mimic LPBF. This research assumes that the energy emitted by the laser interacts with the metal powder with an absorptivity gradient through the layer thickness in order to calculate the thermal history of the process and the evolution of the melt pool dimensions. The obtained results determined that melt pool dimensions follow a thermal pattern, which is caused by the laser scanning strategy of the LPBF process. A new effective width criterion was proposed in the present research in order to accurately relate both calculated and measured dimensions of the melt pool, reducing the relative error of the model and obtaining data scattering with a standard deviation of $\pm 7.21 \mu\text{m}$ and a relative error of 2.92%.

Keywords: Additive Manufacturing, Selective Laser Melting, Melt Pool Dynamics, Laser Powder Bed Fusion.

1. Introduction

Within the additive manufacturing (AM) processes known as powder bed fusion (PBF) technologies, one of the most studied laser based processes is the commonly known Selective Laser Melting (SLM) process. SLM supplies a thin layer ($20\text{ }\mu\text{m} - 1\text{ mm}$) of metal powder on a plate or substrate and afterwards, a high-density power laser melts selective regions of metal powder according to data from a CAD model. Once the laser scanning has been completed, a new powder bed is deposited on the surface of the consolidated metal and the process repeats until the part is completely manufactured [1], as depicted in **Fig. 1**.

Fig. 1. Working principle of powder bed fusion technologies [2].

Understanding the different consolidation mechanisms that occur during the manufacturing process is of great relevance. For instance, in metals, both melting and solidification phenomena are fundamental mechanisms behind the SLM process, which consolidates metal particles in order to manufacture a fully dense and functional part. Most of the common defects associated with SLM are the development of porosity, non-consolidated particles, high level of residual stress and not connected layers [3]. Due to the rapid melting and solidification of the powder bed generated by a mobile heat source (laser), different regions of the workpiece experience repeated cycles of melting/solidification which directly affect its microstructure and final properties [4–7]. Besides, as a result of the nature of the additive process, experimental measurements of the temperature in the workpiece are only possible on easy access surfaces, not in internal regions [6]. Transient thermal fields and histories are previous requirements to establish an understanding of thermal and physical phenomena that alter the metallurgical quality of the final product, such as cooling velocity, solidification parameters, microstructure, residual stress and geometric changes (mainly shrinkage) [8]. For such reasons, numerical simulations are an alternative to determine the temperature evolution

during the SLM process, as well as to achieve a more thorough understanding of the process parameters and defects regarding thermal gradients and parts quality.

Some of the challenges that still need to be overcome when modeling and simulating SLM are: 1) accurate modeling of the heat source and thermal radiation absorptance of the material, 2) consideration of the heat loss during the process, 3) anisotropy of the process and 4) the solidification behavior and phase transformation of the material [9, 10]. Research on 316L stainless steel produced by SLM found that modelling a superficial heat source supplying calorific energy, results in a good agreement between predicted and experimental data, when the laser power and scanning velocity are relatively low. Hussein et al. [11] developed a 3D FE model to simulate the processing of SS316L in SLM. Using the following parameters, laser power and diameter of 100 W and 150 μm , respectively, and scan speed of 100, 200 and 300 mm/s, predicted peak temperatures and relative errors (between experimental and numerical data) less than 2750 K and 3%, respectively. The study carried out by Masmoudi et al. [12] used a similar model for the same material, but considering a laser diameter of 68 μm with a Gaussian power distribution, which resulted in peak temperatures of about 3500 K due to a higher power concentration on the interaction zone between laser and powder bed.

On the other hand, it has been identified that modeling the laser as volumetric heat source is suitable when the workpiece is processed with higher laser power and relatively slow speed scan values [13–18]. The latter produces a higher radiation exposition time from the laser on metal particles, yielding higher thermal energy and thus higher molten pool dimensions. Foroozmehr et al. [13] provided a volumetric heat source model that adopts an optical penetration depth of the laser beam through the powder bed, which is dependent of the powder size and shape. Manvatkar et al. [19] developed a 3D multilayer FE model with a mobile heat source with Gaussian distribution density power and found that melt pool dimensions increase as the SLM process progresses in layers. Li et al. [15, 20] modeled the laser according to Gusarov et al. [14] with high processing speed, achieving relative errors up to 4.15 % and 3.95 % of molten pool width and depth, respectively; considering power and scan speed values of 350 W and 1.14 m/s, respectively. Heeling et al. [16] analyzed the behavior of the melt pool when including effects such as thermal energy absorptance of the powder bed, buoyancy, Marangoni, evaporation and recoil pressure in 316L and IN738LC alloys; the model resulted in relative errors up to 12.5 %. Tran and Lo [17] considered a volumetric heat source based on Gusarov et al. [21] with normal distribution power, and obtained a suitable correlation when the power, diameter and speed scan values are 45 W, 100 μm and 240 mm/s, respectively; the model resulted in relative error of 3.45 % in molten pool width. Luo and Zhao [18] presented an efficient simulation scheme in terms of

computational cost through a dynamic refinement meshing according to laser position on the powder bed and achieved relative errors of width and molten pool depth of 2.3 % and 7.1 %, respectively.

However, a comprehensive study of the morphology of melt pools during SLM has not been studied yet, neither the description of direct thermal phenomena that affects melt pool dimensions, which are an important indicator to detect critical thermal zones. The aim of this work is to evaluate the temperature behavior over time and dimensional temperature distribution during the SLM process to describe the dynamics of the melt pool dimensions. This study presents a non-linear and transient 3D FE model to simulate the SLM process of SS316L in order to predict the thermal response of the system. The model considered most of the processing parameters involved in SLM and inherent properties to the material, such as absorptance, particle size, thermal conductivity, heat capacity and enthalpy (in liquid, solid and powder state). The laser model is contemplated as a volumetric heat source, which has a dynamic radiation absorptance depending on the thickness of the powder bed. Finally, an anisotropic enhanced thermal conductivity methodology was introduced for temperatures above the melting point due to convection produced inside the molten pool (Marangoni effect).

2. Thermal modeling

In order to model SLM, the energy conservation and heat conduction equations are considered, resulting in the thermal equilibrium equation for tridimensional heat transfer in a material with anisotropic thermal properties as described according to Eq. 1 [10].

$$Q(\mathbf{r}, t) - \rho C_p \frac{dT}{dt} + \nabla \cdot [k(T) \nabla T] = 0 \quad (1)$$

where ρ is the material density (kg/m³), C_p is the isotropic heat capacity (J/kg-K), T is temperature (K), t is time, Q is a mobile heat source (W/m³), ∇ is a divergence operator and r is relative reference or spatial coordinate in the system volume domain, and k is the material's thermal conductivity (W/m-K) in function of temperature.

Due to material phase changes and thermophysical properties in SLM, a non-linear implementation is necessary [6, 10, 22]. Moreover, a special approach is presented for those material properties such as density, thermal conductivity, and enthalpy which depend on whether the state of SS316L is as powder, solid or liquid. The thermophysical properties of the present alloy are extracted from Mills

[23]. However, the powder bed is a mixture composed of metal particles and voids among them occupied by inert gas. Therefore, powder bed density ρ_{pwd} can be described as a rule of mixtures between metal particles ρ_s and argon ρ_g according to Eq. 2 [13].

$$\rho_{pwd} = \varepsilon \rho_g + (1 - \varepsilon) \rho_s \quad (2)$$

The thermophysical properties of SS316L are depicted in **Fig. 2**. The density behavior of both powder and solid state can be observed in **Fig. 2a**, where a spike is observed in the transition region. **Fig. 2b** shows the thermal conductivity for metal powder and solid state and **Fig. 2c** presents the heat capacity and enthalpy of 316L steel alloy. The thermal conductivity of the metal powder was determined according to the equations presented by Sih and Barlow [24, 25].

Fig. 2. Thermophysical properties of 316L steel alloy, a) Metal powder and solid densities, b) Metal powder and solid Thermal conductivities and c) Heat capacity and enthalpy.

To compute the powder's thermal conductivity k_p , the morphology of particles is assumed to be spherical and behave according to Eq. 3, where k_g is defined as the thermal conductivity of inert gas surrounding the particles [26], ε is the powder bed porosity, k_s is the thermal conductivity of solid 316L steel. The emission of the total radiation amongst particles inside of the powder bed is calculated with Eq. 4, which considers the fraction of pores on the surface A_H (Eq. 5) and ϵ_H is the emissivity of

vacancies over the powder surface (Eq. 6), and k_r defines the heat transfer accounted for radiation among particles of diameter D_p according to Eq. 7, where σ defines Stefan-Boltzmann constant.

$$k_p = k_g \left\{ (1 - \sqrt{1 - \varepsilon}) \left(1 + \varepsilon \frac{k_r}{k_g} \right) + \sqrt{1 - \varepsilon} \left[\frac{2}{1 - \frac{k_g}{k_s}} \left(\frac{2}{1 - \frac{k_g}{k_s}} \ln \frac{k_s}{k_g} - 1 \right) + \frac{k_r}{k_g} \right] \right\} \quad (3)$$

$$\epsilon_p = A_H \epsilon_H + (1 - A_H) \epsilon_s \quad (4)$$

$$A_H = \frac{0.908 \varepsilon^2}{1.908 \varepsilon^2 - 2\varepsilon + 1} \quad (5)$$

$$\epsilon_H = \frac{\epsilon_s \left[2 + 3.082 \left(\frac{1 - \varepsilon}{\varepsilon} \right)^2 \right]}{\epsilon_s \left[1 + 3.082 \left(\frac{1 - \varepsilon}{\varepsilon} \right)^2 \right] + 1} \quad (6)$$

$$k_r = \frac{4\epsilon_p \sigma T^3 D_p}{1 - 0.132 \epsilon_p} \quad (7)$$

Simulations of heat transfer by convection require calculations of mass velocity fields, which are difficult and computationally demanding. However, there are evidences that show this accelerated heat transfer is not taken into account in the molten pool which may result in inaccurate temperature records and cooling velocity [6, 27].

It is possible to consider two important effects due to thermal dependence of thermophysical properties developed inside the melt pool. The first effect is the thermal capillarity convection phenomenon or so-called Marangoni [28, 29], and the second effect is the buoyancy by density change. The convection by thermo-capillarity occurs when a superficial tension gradient is developed inside the flow, as the surface tension of the liquid metal is higher compared to other liquids (due to a combination of dispersion force and metallic bonds), the metal tends to flow [30].

Because of the nature of the FE model, it is hard to solve the Navier-Stoke equations. However, some researchers [27, 31, 32] have used an enhanced thermal conductivity approach to include the heat transfer by convection in the molten pool which interacts with the powder bed. Thus, rather than

solving intrinsic Navier-Stoke equations, the energy equation is determined by the introduction of an enhanced thermal conductivity factor k''_{ii} by the Eqs. 8 and 9.

$$k''_{ii} = F_{ii} k \quad (8)$$

where k is defined as the isotropic thermal conductivity related to the temperature, the subscript ii is the spatial coordinate and F_{ii} the anisotropic enhanced factor for a given spatial coordinate described by Eq. 9. Based on several test simulations [33], it was concluded that the most suitable enhanced factor has the setup $(F_{xx}, F_{yy}, F_{zz}) = (1, 5, 10)$.

$$F_{ii} = \begin{cases} 1, & \text{if } T < T_f \\ \text{Multiplier factor}, & \text{if } T > T_f \end{cases} \quad (9)$$

During SLM, temperature changes due to the heat flux are attributed to sensitive heat. Whilst the release or absorption of thermal energy at constant temperature is due to phase change or latent heat of the material. Both thermal phenomena are introduced by enthalpy H [11], in volume terms, defined by Eq. 10.

$$H = \int \rho(T) C(T) dT \quad (10)$$

Various approaches have been proposed to model the laser as a mobile heat source [13, 28, 31, 34–37] for SLM SS316L. However, laser considered as a surface heat source is acceptable if the power value is less than 100 W [11, 12]. Otherwise, modeling the laser with a volumetric heat source is suitable for high power and speed values [13, 15–18, 20]. The analysis achieved by Gusarov et al. [14, 21] resulted in a deduction of a dynamic absorptivity model, which consists in considering a volumetric heat source along with two factors. The first factor is the absorptivity, which takes place when the energy is absorbed from the powder bed surface. The second factor is the reflected radiation, which enters inter-particles voids (pores) that are placed beneath the powder bed surface.

The absorptivity A is specified as the net density rate of absorbed radiation energy flux by the powder bed to the laser power density and its behavior is based on the powder bed thickness [14]. Therefore, the laser radiation travels through the powder bed pores to an effective depth of various particle

diameters due to multiple diffuse reflection. Consequently, laser energy is not only supplied on the powder bed surface but through the powder bed thickness (z direction) according to Eq. 11

$$A(z) = \frac{\rho_r a}{(4\rho_r - 3)D} \left\{ (1 - \rho_r^2) e^{-\lambda} [(1 - a) e^{-2a\beta z} + (1 + a) e^{2a\beta z}] - (3 + \rho_r e^{-2\lambda}) \right. \\ \left. \times \{ [1 + a - \rho_r(1 + a)] e^{2a(\lambda - \beta z)} + [1 - a - \rho_r(1 + a)] e^{2a(\beta z - \lambda)} \} \right\} \quad (11) \\ - \frac{3(1 - \rho_r)(e^{-\beta z} - e^{\beta z - 2\lambda})}{4\rho_r - 3}$$

where β is defined as an extinction coefficient, λ is defined as the effective penetration thickness of the laser energy (which is equivalent to the thickness of the layers) and ρ_r describes the metal powder's hemispherical reflectivity (when in dense state). Introducing ρ_r determines the presumption that the reflection is diffuse and non-specular. The variables D , a , λ and β are determined using Eqs. 12 to 15.

$$D = (1 - a)[1 - a - \rho_r(1 + a)]e^{-2a\lambda} - (1 + a)[1 + a - \rho_r(1 - a)]e^{2a\lambda} \quad (12)$$

$$a = \sqrt{1 - \rho_r} \quad (13)$$

$$\lambda = \beta L \quad (14)$$

$$\beta = \frac{3(1 - \varepsilon)}{2\varepsilon D_p} \quad (15)$$

Table 1 enunciates the parameters used to determine the powder bed's dynamic absorptivity, in which the thickness and the particle diameter are characteristic data of the process, see **Fig. 3**.

Table 1. Dynamic absorptivity parameters.

Parameter	Value	Ref.
Hemispherical reflectivity ρ_r	0.682	[38]
Thickness layer L (μm)	30	-
Particle diameter D_p (μm)	25	-
Powder bed porosity ε	0.48	[39]

The behavior of the dynamic absorptivity distributed in the depth of the powder bed is represented in **Fig. 3a**. Gusarov et al. [14] proposed that the absorbed energy density by the metal powder bed caused by the laser irradiance is assumed as a volumetric heat source based on dynamic absorptivity (Eq.

16), where the dA/dz component is the absorptivity exchange rate of the powder bed through the thickness, see **Fig. 3b**.

Fig. 3. a) Absorptivity A through the powder bed thickness (z) and b) absorptivity exchange rate through the powder bed thickness (z) [33]

The Q_0 component is the surface power density with Gaussian distribution which is expressed in Eq. 17, in which the laser power is represented as P , the normal distribution factor as f ($f=1$), the scan speed as v and the laser radius as r_b . The x -direction is considered parallel to the movement of the heat source, whereas the y -direction is considered as normal to the laser path [40].

$$Q(x, y, z) = -Q_0(x, y) \frac{dA(z)}{dz} \quad (16)$$

$$Q_0 = \frac{fP}{\pi r_b^2} \exp\left(-f \left(\frac{y^2 + (x + vt)^2}{r_b^2}\right)\right) \quad (17)$$

3. Numerical simulation

The model and geometry used for this study are shown in **Fig. 4**. The schematic points out the three main domains. One represents the base plate, also known as substrate, whose main function is to support the powder bed and consolidated part in the SLM process. Another domain represents the metal powder, and the last one is the solidified metal by the laser action.

Fig. 4. Schematic of the model including the substrate, powder and workpiece (measurements in μm).

The selected dimensions prevent undesirable effects due to the boundary conditions of non-heat transfer on the lateral faces and guarantee a suitable thermal interaction between the solid parts and powder. A 3D FE model was created in ANSYS MECHANICAL APDL® with a high refinement mesh at the interaction area between laser/powder (central region), a $10\mu\text{m}$ element size was defined and SOLID70 element type characterized by its 3D thermal conduction capacity was selected. SOLID70 elements consists of 8 nodes and a one degree of freedom (temperature). Because of the additive nature of the process, the *Element Birth and Death* function is used to activate layers during the SLM simulation.

The laser scanning strategy is zigzag according to **Fig. 5**; six paths per layer and the laser/material interaction zone is $500 \times 620 \mu\text{m}^2$. Due to the discrete nature of the model, the laser movement has been discretized; it advances each $20 \mu\text{m}$ in the indicated direction with an irradiance time of $86.96 \mu\text{s}$ (calculated from the scanning speed).

Fig. 5. Scanning strategy per layer. Dimensions in μm .

Fig. 5 contains a series of red circles (laser spot) and each one is spaced $20\ \mu\text{m}$ away (point distance). Each path consists of 22 spots, 132 spots per layer and 660 spots in total (5 layers). The process parameters were established according to manufacturer recommendation.

4. Experiments

A SLM Solutions 280 machine was used in this study, which is equipped with an IPG fiber laser system of 400 W nominal power, wavelength of 1065 nm and spot diameter of $70\ \mu\text{m}$. The selected metallic powder was SS316L and test samples with dimensions of 10x10x10 millimeters were manufactured. Test samples were manufactured in an inert atmosphere using argon on the AM system. The specimens were traditionally cut in the perpendicular plane to the thickness. Afterwards, samples were prepared with standard metallographic procedures and an electrochemical attack was performed to reveal the microstructure. The etchant used was composed by a mix with a proportion of ten grams of oxalic acid and a hundred milliliters of distilled water, then 6V (Direct Current) were applied for 60 seconds to expose the microstructure. A Zeiss optical microscope AX10 was used to examine the microstructure. The SLM processing parameters are enlisted in **Table 2**.

Table 2. SLM process parameters for the numerical simulation.

Parameter	Value
Laser power P (W)	400
Point distance (μm)	20
Laser diameter D (μm)	70
Hatch space HS (mm)	110
Scan speed (mm/s)	230
Number of layers	5

Experimental measurements of the obtained melt pools of the test samples were performed to estimate the temperature profile. The obtained microstructural characteristics of the test samples can be observed in **Fig. 6**. The obtained morphology of the melt pool determines that its width and depth can be directly related with those regions that were exposed to temperatures above the melting point. The measured width (y-axis) and depth (z-axis) can be further examined in contrast with the simulation results. The obtained melt pool can be considered as a series of ovoids, which are commonly generated by the laser beam.

Fig. 6. Microstructure of SLM samples.

5. Results and Discussion

The implementation of a volumetric heat source proposed by Gusarov et al. [14, 21] resulted in the normal distribution of surface power Q_0 , which is presented in **Fig. 7**. For this condition, the laser power and diameter are 400 W and 70 μm , accordingly. Based on the rate of change of dynamic absorptivity dA/dz showed in **Fig. 3** and power Q_0 , it is possible to calculate the power distribution through the powder bed thickness. The absorbed power distribution based on Gusarov model is observed in **Fig. 8** for 10 μm (element size) increments in z -direction.

Fig. 7. Laser irradiance $Q_0(x,y)$ of 400 W.

Fig. 8. Absorbed power distribution based on Gusarov model.

Once the temperature histories are obtained with thermal effects from previous layers and based on the study of Luo and Zhao [18], the last layer of the powder bed was examined. **Fig. 9** illustrates the thermal distribution of the powder bed surface at spots 539 and 550, respectively. As observed, thermal histories developed during the simulation process did not reach the boiling point of 316L steel (3200 K).

Fig. 9. a) Thermal distribution on surface powder bed at the last layer (spot 539) and b) Thermal distribution on surface powder bed at the last layer (spot 550).

For the measurement of the simulated melt pool, nodes with temperatures higher than melting point (≥ 1678 K) were selected and located in the laser irradiance region. This can be seen in **Fig. 10**, where a considerable melt pool depth is observed. Using this methodology, all three dimensions of the melt pool (width, length and depth) were calculated in the last layer (132 molten pools). **Table 3** compares both the mean and standard deviation of the experimental and simulated data highlighting that the relative error is close between both measurements.

Fig. 10. 3D geometry of molten pool. Temperature in K.

Table 3. Numerical and experimental data on molten pool dimensions in last layer.

	Width (μm)		Depth (μm)	
	Mean	S	Mean	S
All considered pools	167.04	29.99	99.02	10.40
Experimental	159.07	16.81	98.57	13.59
Error (%)	5.01	-	0.46	-

Thermal histories were analyzed in those nodes located in critical zones, where a thermal accumulation caused by the scanning strategy (zigzag) was observed. **Fig. 11** shows the critical regions using red circles with a nomenclature from A to E. Thermal histories through time can be seen in **Fig. 12** during the processing of last layer, where the second digit corresponds to layer number.

Fig. 11. Critical spots to analyze in thermal histories of SLM process.

Fig. 12. Temperature histories of thermally critic areas at the last layer.

From **Fig. 12** can be deduced that while the laser consolidates particles in the last layer, a thermal affectation exists in nodes located in previous layers, obtaining a melt pool depth of up to 4 layers. The last layer can be seen as an example, where thermal histories from A1 to A4 surpass the melting line. Therefore, the portion above the melting temperature indicates that the metal is in a liquid phase and the projection length of this portion to the horizontal axis corresponds to the liquid state (~ 1 ms) for nodes at the last layer.

5.1 Dynamic melt pool and effective width criterion

Following the dynamic phenomena discussed above, the change in melt pool dimensions throughout the manufacturing process was further investigated. The behavior of the melt pool width through the laser path in the last layer was analyzed as shown in **Fig. 13**, where the horizontal axis corresponds to the absolute position of the laser (see **Fig. 4**) and vertical axis to the melt pool width. The first scan path initially showed an increase and transient behavior of the melt pool width until a permanent response was reached ($\sim 130 \mu\text{m}$) due to the cooling of the powder bed. Subsequently, once the powder bed was thermally affected by the first scan path, all subsequent laser paths started with a maximum melt pool width due to the laser scanning strategy, but the behavior tends to decrease until reaching a steady state ($\sim 152 \mu\text{m}$). This behavior was also reported by Weirather et al. [41] who recorded the changes of the melt pool length, depth and width numerically determined by simulating the distance covered by the laser.

Fig. 13. Behavior of the molten pool width through path laser.

Fig. 14 shows the melt pool width evolution for the 1st and n th laser scan. This curve represents an average curve from 2nd to 6th laser scanning. It can be observed in **Fig. 14** that an exponential regression was carried out in both curves to consider the thermal system as a transient and steady-state response. The equations shown in **Fig. 14** are composed by two terms: the first term in the right-hand side of the equation corresponds to the transient response (time exponential) and the second one represents the steady-state response (constant value). The time constant τ is one characteristic of the curves that at $t = \tau$ the $w(t)$ reaches $1 - e^{-1}$ of the steady-state response (i.e., 63.2 %) and at $t = 4\tau$ reaches 98.2 %. For purposes of this study, time constants for the first and n th scans are 171 μ s and 283 μ s, respectively.

Fig. 14. Dynamic molten pool width in 1st and n th scan.

For melt pool dynamics, Weirather et al. [41] proposed the following net melting rate in relation to the laser path, which can be defined in terms of volume.

$$\frac{dV}{dt} = \left(\frac{dV}{dt}\right)_f - \left(\frac{dV}{dt}\right)_s \quad (17)$$

where $(dV/dt)_f$ defines the volume of particles transforming from solid to liquid in a certain amount of time, whereas $(dV/dt)_s$ describes the volume rate associated with the solidifying liquid. If $dV/dt > 0$, the melt pool size increases. Contrarily, $dV/dt < 0$ relates to a shrinking size, whereas $dV/dt = 0$ points out the melt pool's steady state. **Fig. 15** shows the net melting rate supporting the sense of transient response at the beginning of the scan in both cases, although the n th scan is obtained a higher rate due to the thermal influence caused by the previous scan (i.e., n th – 1 scan).

Fig. 15. Behavior of net melting rate at 1st and nth scan in last layer.

Based on the melt pool width response in steady state discussed above and the fact that melt pool measurements were carried out in central areas of the samples, a new evaluation between numerical and experimental melt pool dimensions was proposed, in which the simulated widths were considered at $t > 4\tau$. **Table 4** shows an average width and standard deviation for all considered melt pools and those at time $t > 4\tau$ in n th scan and last layer. It was observed that for a criterion of melt pool width in steady state, a standard deviation of $\pm 7.21 \mu\text{m}$ and relative error of 2.92 % were determined, drastically reducing the data scattering versus all considered pools.

Table 4. Comparison between simulated and experimental melt pool width in last layer and nth scan.

	Width (μm)		
	Mean	S	Error (%)
Experimental	159.07	16.81	Ref. data
All considered pools	167.04	29.99	5.01
Pools at time $t > 4\tau$	154.42	7.21	2.92

There are several approaches to model the melt pool width; the analytical model derived from the Rosenthal equation and estimated by Tang et al. [42] is the following (Eq. 18):

$$T_f = T_0 + \frac{Q}{2\pi kr} \exp\left(-\frac{V(\xi + r)}{2\alpha}\right) \quad (18)$$

where T_f is defined as the alloy's melting point, T_0 represents the temperature of the preheated substrate, Q_{abs} is the absorbed power by the alloy, k indicates the material's thermal conductivity, V the laser scan speed, and α the material's thermal diffusivity. The terms r and ξ refer to the melt pool size and shape, as shown in **Fig. 9**, in which ξ represents the gap from the heat source, which is determined in the same trajectory in which the laser beam travels, and $r = (\xi^2 + y^2)^{0.5}$ indicates the gap to the melt pool edge from the center of the heat source. The latter, where the highest melt pool width is located, $r = r^*$ in accordance to **Fig. 16**.

Fig. 16. Schematic representation of the melt-pool dimensions (top view; frame of reference travels with the laser). The laser is concentrated at the y and ξ axes intersection [42].

In order to simplify the previous expressions, constants M and N are used and are defined next:

$$M = \frac{V}{2\alpha} \quad (19)$$

$$N = \frac{2\pi k}{Q_{abs}}(T_f - T_0) \quad (20)$$

Substituting in the Rosenthal equation and after mathematical deductions [42] yields

$$1 + \ln(r^*M) = -\frac{\ln(r^*M)}{r^*M} \quad (20)$$

However, Tang et al. [42] assumed that the term $-\ln(r^*M)/r^*M \approx 0$ while, for purposes of this study, a value of 0.29 was estimated according to thermal properties and some process parameters summarized in **Table 5**.

Table 5. Thermal properties of 316L steel at melting temperature and some process parameters

T_f	T_0	Q_{abs}	V	C_p	k	ρ	α
(K)	(K)	(W)	(mm/s)	(J/kg-K)	(W/m-K)	(kg/m ³)	(m ² /s)
1697	373	52	230	830	28.5	6881	4.99x10 ⁻⁶

Additionally, a new relationship between r^* and φ^* and the half-width was found.

$$\sin \varphi^* = \frac{\sqrt{2r^*M + 1}}{r^*M + 1} \quad (21)$$

$$\frac{W}{2} = r^* \sin \varphi^* \quad (22)$$

Solving Eq. 20 to 22 an estimated melt pool width of $W = 150.93 \mu\text{m}$ is determined, which was graphed in **Fig. 14** as a red and horizontal dashed line. There is a relationship between the estimated melt pool W and steady-state response $w(t)$ in n th scan where this latter converges approximately in W and shows the permanent regime of $w(t)$.

6. Conclusions

This research analyzed the modeling of a thermal process to calculate temperature histories and the behavior of a SS316L manufactured by SLM. A non-linear and transient FE model was applied to predict the thermal response of the material in each of its states (powder, liquid and solid). The model included the process parameters that are involved in SLM as input data.

For a deeper analysis, temperature histories in critical zones were monitored due to thermal accumulation caused by the selected scanning strategy (zigzag). This analysis was carried out in each layer in which there is no record of temperature above the boiling point. For the 4th and 5th layers, those critic zones showed several cycles of fusion/solidification, affecting up to four previous layers and lifetime of approximately ~1 ms of molten material.

A dynamic thermal response was identified and characterized, specifically on the melt pool dimensions. This dynamic behavior on the melt pool width was divided into two types of laser scans: the first and n th scans which behave differently and were analyzed separately by exponential regressions. Both curves showed a transient and steady-state melt pool width response whose response regimes were characterized numerically, and a relationship was found between the steady-state response $w(t)$ of n th scan and the estimated molten pool width by the expressions derived from Rosenthal equation.

From previous work, a new comparison between simulated and experimental melt pool dimensions was evaluated, in which the simulated widths were considered as long as the response was in steady state, in n th scan, and neglecting widths molten pool in the first scan. This comparison raised a new effective width criterion in order to more accurately relate calculated and measured dimensions of the melt pool.

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Statements and Declarations

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- All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

b. Conflicts of interest/Competing interests

- The authors have no relevant financial or non-financial interests to disclose.
- The authors have no competing interests to declare that are relevant to the content of this article.
- The authors have no financial or proprietary interests in any material discussed in this article.

c. Availability of data and material

- The data presented in this study are available upon request to the corresponding author.
- All the data is presented within the article.

d. Code availability

- The code used to obtain the FEM results in this study is available upon request to the corresponding author.

e. Ethics approval

- The authors confirm that this manuscript has not been submitted to other journals, is not previously published, or in press.
- The authors confirm that all the presented information is original.

f. Consent to participate

- Not applicable

g. Consent for publication

- Not applicable

h. Authors’ contributions

- Author contributions: Methodology – JTT, LRO, CG, OLB; Conceptualization – OLB; Validation – JTT; Formal analysis – JTT; Investigation – JTT; Writing original draft – JTT; writing review and editing – LRO, CG, PZR, OLB; visualization – JTT, OLB; supervision – PZR, OLB; funding – PZR.

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