IV International Conference on Simulation for Additive Manufacturing
Sim-AM 2023
E. Rank and S. Kollmannsberger (Eds)

NUMERICAL MODEL FOR THE LASER METAL DEPOSITION ADDITIVE MANUFACTURING PROCESS: MULTIPHYSICS MODELING AND EXPERIMENTAL VALIDATION

G. DALI[*], M. RACHIK[†], J. FAVERGEON[†] AND S. GAIED[‡]

[*†] Laboratoire Roberval
Université de technologie de Compiègne
Centre Benjamin Franklin, 60200 Compiègne, France
e-mail: ghassen.dali@utc.fr, web page: www.utc.fr

[‡] ArcelorMittal Global R&D Montataire
F-60160, Montataire, France
web page: www.france.arcelormittal.com

Key words: numerical simulations, Additive manufacturing (AM), computational modeling

Abstract. Metallic Additive Manufacturing (AdM) technologies (3D printing) is rapidly spreading to a variety of industrial applications. In recent years, advances in AdM have gradually transformed the way in which manufactured products are designed and produced. It enables easy manufacturing of complex shaped parts with high performance, less material waste and short development cycle. Laser Metal Deposition (LMD) is one of the processes in this growing field. This process can produce high performance parts by the injection of powders into a melt-pool created by a laser heat source. However, the LMD is complex and several defects may appear during the printing process. In this context, numerical simulation could be a helpful tool to describe the involved physical phenomena and then to predict the impact of process parameters on the material state. Such numerical tool can predict the heat exchanges and the fluid flow within the molten pool enabling defect prediction and process optimization. In this work, a multi-physics numerical model of the LMD process, at a mesoscopic scale, (i.e. at the layer thickness scale) is developed to predict thermal cycles during fabrication, as well as the complex relationships between part construction and operating parameters. For this purpose, the finite element code COMSOL Multiphysics is used. The developed model takes into account fluid flow and heat transfer in the different phases (gas, substrate and melt pool). As a key feature, the developed model simulates the growth of the track using the generation of droplets when the powder flow is intercepted by the laser beam. Material addition, interface tracking, and strong topological changes are handled using the level set technique. The numerical results are compared to the experimental results for validation purposes. This validation includes the comparison between the predicted molten pool cross-section and measurements from macrographs and high-speed videos.

1 INTRODUCTION

Laser Metal Deposition (LMD) process is one of the most promising technology in the additive manufacturing fields, it provides a possibility to produce 3D structures from CAD drawings by a sequence of layer deposition. During an LMD process, a multi-flow gas circulates inside a deposit nozzle to form a powder jet, which feeds a molten pool created by the interaction of a laser irradiation on the surface of a metallic substrate. Thus, the global volume is raised and the first layer is formed. The next layer is then built on the previous one, resulting in a 3D part.

A global and comprehensive physical understanding of the LMD process is quite complicated because it addresses a large number of parameters such as: the powder stream, the laser beam power and velocity. These parameters and their interactions are not always well controlled and understood. The literature is replete with analytical and numerical studies dealing with different aspects of LMD. However, the reported models are very different in terms of accuracy and complexity. The main difference between the proposed models has to do with the heat sources modelling, the different phases handling or the free surface and the integration of sub-process models like the powder jet.

When it comes to LMD modeling, the research works reported in literature focus mainly on the powder stream or the melt pool analysis. The models dealing with the powder streams investigates the powder flow as it directly affects the spatial powder distribution, the beam attenuation, the gas flow, the velocity and the temperature of the particles. These models are validated and compared with complex computational fluid dynamics (CFD) models [1] and [2]. The models dealing with the melt pool modeling include several analytical models that handle the formation of wall geometries by considering a predefined analytical function of the final shape like those reported in [3]–[5]. They also include numerical models that use the element activation (“birth”) approach [6], [7]. More sophisticated models take into account fluid flow and the free surface movement using tracking surface technics such as level-set, phase-field, Volume Of Fluids (VOF) or the Arbitrary Lagrangian Eulerian method (ALE). The ALE method is used by Morville et all [8] to track explicitly the dynamic shape of the melt pool surface. Their model predicts, in a realistic manner, the growth of thin walls and it capture the characteristic shapes near the wall boundaries. The level-set method was used by Han et al [9] as well as Qi et al [10] to simulate several track formations. Ibarra-medina et al [11] and Bayat et al [12] used a continuum models based on the VOF method. The model couples the powder particle flow with the melt pool simulation.

Our work is an attempt to develop a full thermohydraulic model that take into account the most relevant physical phenomena for the LMD process simulation. Particular attention is paid to the material source (powder feeding) modeling. As it is difficult to track each individual particle, the incorporation of the powder into the melt pool is tracked using droplets. This is a key feature of the model we developed using COMSOL Multiphysics software. The model is used to predict heat and fluid flow during LMD process, as well as the complex relations between the material deposition and the operating parameters.

2 MODELING STRATEGY OF THE LMD PROCESS

Given the difficulty of simulating and tracking each powder particle and its interaction with the laser and the molten pool, a novel approach has been adopted. It consists in tracking droplets instead of particles. Each droplet is an agglomeration of particles and each particle is interacting in its own way with the laser source. The droplet temperature when it reaches the melt pool is supposed uniform and it results from the particles thermal history. The transition from particles to droplet is illustrated in (fig.2).

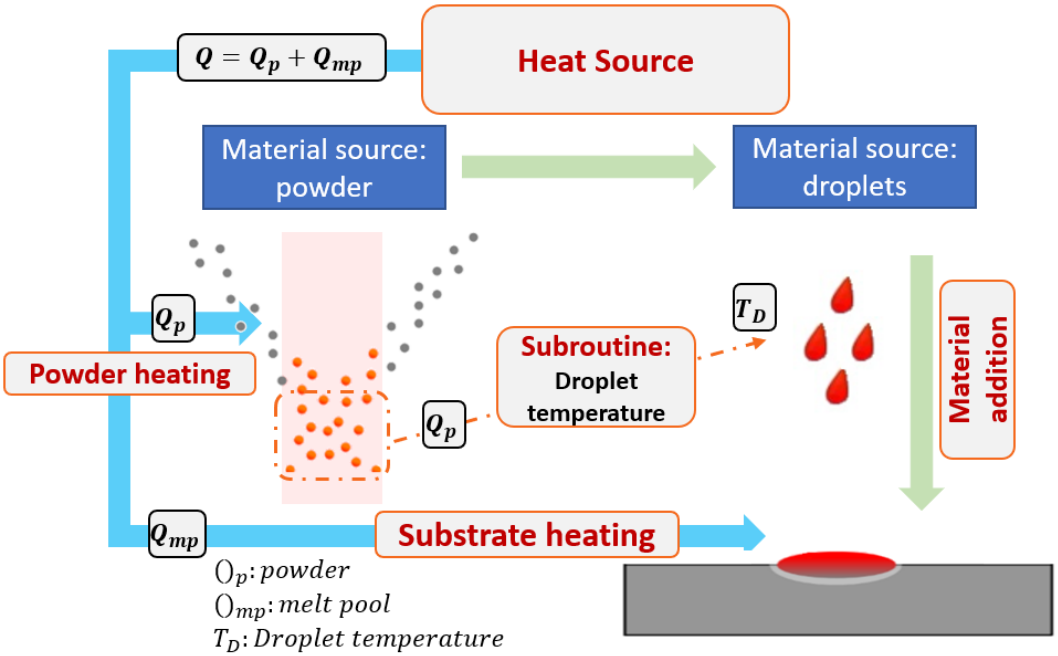

Figure 1: A schematic diagram of the adopted approach for the LMD simulation

The material addition or the droplet generation rate, used in this study, was determined using the mass conservation law. The droplet generation volume V_g can be calculated from the powder mass flow rate P_f and the droplet detachment frequency f_d using the following equation:

$$N\rho_d V_d f_d = \eta_p P_F \tag{1}$$

where ρ_g represents the density of the droplet and N donates the deposited droplet generation rate. η_p represents the powder catchment efficiency, which depends on the process parameters and is measured by experiments. The main goal here is allowing the use of a relatively large grid size for the calculation domain, without affecting the accuracy of the simulation results.

The heat flow problem is split into two parts. The first one deals with the temperature field and the fusion condition inside the molten pool. The second part entails the calculation of droplet temperature, which is derived from the thermal history of the particles making up the droplet. To achieve this, a dedicated algorithm is employed to assess the laser energy absorbed by the powder during the mass addition phase and convert it into an average initial temperature assigned to the deposited droplets. The ultimate goal is to compute the temperature of the droplets and establish the boundary conditions for the numerical model.

3 GOVERNING EQUATIONS

The physical model is implemented in COMSOL Multiphysics® 6.1. It tracks the interface and solves energy conservation and the Navier-Stokes equations in the entire domain for a laminar, Newtonian and incompressible flow.

With these assumptions, the governing equations can be written as follows:

Energy conservation equation:

$$\rho \mathrm{C_p}\left(\frac{\partial T}{\partial t} + (\mathrm{u}\,.\nabla)T\right) = \nabla.(\mathrm{k}\nabla \mathrm{T}) + Q_{laser} \tag{2}$$

$$Q_{laser} = \eta\alpha \frac{2P_{laser}}{\pi r_{laser}^2} exp\left(\frac{-2(x^2+y^2)}{r_{laser}^2}\right)^4 \tag{3}$$

With ρ is the density, C_p is the heat capacity, k is the thermal conductivity, u is the velocity and T is the temperature. The heat input source Q_{laser} is considered as a homogeneous laser heat flux with a top hat distribution where η is the energy efficiency, α is the absorptance. r_{laser} and P_{laser} respectively represent the laser beam radius and the laser power. The laser intensity is counterbalanced by three boundary conditions, namely, radiation and convection within the metal phase.

$$-\mathrm{n}.(-\mathrm{k}\nabla \mathrm{T}) = -\epsilon\sigma(T^4 - T_0^4) - h(T - T_0) \tag{4}$$

Where ϵ the total emission coefficient, h and σ are respectively the convection heat transfer coefficient and the Stephen Boltzmann constant and T_0 the ambient temperature.

Droplet temperature computation:

As mentioned previously, the temperature of droplet is estimated from the thermal history of the particles that make it up. The complex laser-powder interaction is not explicitly integrated; instead, all the laser energy which is absorbed by the powder during the mass addition process is converted into an average initial temperature to the deposited droplets. The procedure used to determine the temperature of a droplet is described below:

1. Estimate the volume droplet from the powder flow rate and the droplet detachement frequency.
2. Use a random distribution of different sizes and trajectories of powder particles injected from the nozzle (ri, θi). This allow for estimating the random character of the powder projection process.
3. Heat exchange analysis of particles travelling from the nozzle to the molten pool and determination of its temperature. Another energy equation, based on the thermodynamics laws, is solved to find the temperature of the powder particles.

$$m_p C_p \frac{dT}{dt} = A'_p \beta Q_{laser} - A_p \epsilon\sigma(T^4 - T_0^4) - A_p h(T - T_0) \tag{5}$$

   Where m_p is the particle mass, A_p is the particle surface area and A'_p is the projected surface area of the powder particles seen by the laser. β is the absorption rate and Q_{laser} is the energy distribution of the laser beam described in (3).
4. Operations 2 and 3 are repeated until reaching the volume of the droplet.
5. The temperature of the droplet is the average of the temperatures of the particles

that make it up weighted by their volumes.

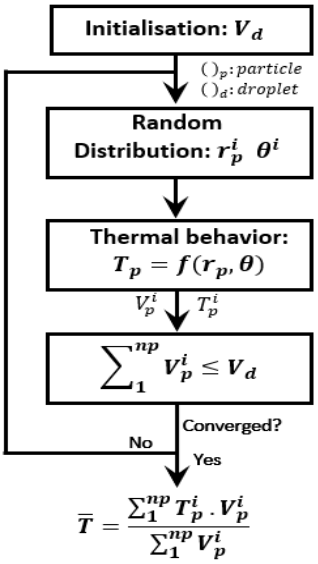

Figure 2: Algorithm for the droplet temperature calculation

Mass and momentum equation:

$$\rho \frac{\partial u}{\partial t} + \rho(u.\nabla)u = \nabla\left[-PI + \mu\left((\nabla u + (\nabla u)^T)\right)\right] + Ku + F_m \quad (6)$$

$$\nabla(u) = 0 \quad (7)$$

Where P is the pressure, μ is the dynamic viscosity, I is the unit tensor, F_m is the volumes forces and K is the Darcy's penalization law. It is used to model the solid / liquid transition in the metal phase.

$$K = C_1 \frac{(1 - f_{liq})^2}{f_{liq}^3 + C_2} \quad (8)$$

where C is a constant enough large to ensures the decrease of the velocity field in the solid region, b is a relatively low constant introduced to avoid division by zero.

The model also integrates volume forces introduced in (6) such as surface tension, thermocapillary convection (Marangoni effect) and buoyancy force. They can be formulated as follows:

$$F_{surface\ tension} = \sigma \kappa n \quad (9)$$

$$F_{marangoni} = \sigma[\nabla T - (\nabla T.n)n] \quad (10)$$

$$F_{buoyancy} = \rho g \beta (T - T_0) \quad (11)$$

Where σ is the surface tension coefficient, κ is the curvature and n is the normal vector to the interface. g, β and T_0 represent respectively, the gravity, the thermal expansion rate and the reference temperature. The buoyancy force (body force) is modeled based on the Boussinesq approximation.

Level set method:

The level set method is used to simulate the metal transfer. It tracks the moving interface between the metal phase and the gas. The substrate, the generated droplets and the molten

metal are considered as a unique metal phase. The domain is defined using a variable ϕ which takes the value 0 in gas, 1 in metal and an isovalue ϕ = 0.5 at the interface. The displacement of the interface is transported with the fluid velocity by solving the following transport equation:

$$\frac{\partial \phi}{\partial t} + u \,.\nabla(\phi) = \gamma_{ls} div\left(\varepsilon_{ls}\nabla\phi - \phi(1-\phi)\frac{\nabla\phi}{|\nabla\phi|}\right) \tag{12}$$

Where γ_{ls} is the reinitialization speed (or stability) of the level set function and ϵ_{ls} is the interface thickness controlling parameters.

4 RESULTS AND DISCUSSION

The model is used to provide information about temperature and velocity field at the first stages of the metal transfer during an LMD process. It can capture the influence of the process parameters on the process observable results.

The laser beam starts irradiating the base plate for a short duration of 0.2s, the time to from the molten pool. This first step is necessary since the first droplet must falls in a liquid bath, but this step is no longer required for the rest of the process. Fig. 3 shows four snapshots of the temperature field in the droplets and the melt pool at different times. The illustrations show the first moments of the process with the addition of several droplets. Initially, it is observed the first drop forming through the upper gas boundary for a period of time. When the desired droplet volume is reached, the droplet detaches to fall in the melt pool. Then, the new droplet grows to restart a new supply cycle as it can be seen. The last illustration show that the melt pool reaches a stable condition after some time and its total volume remains almost constant until the end of the track.

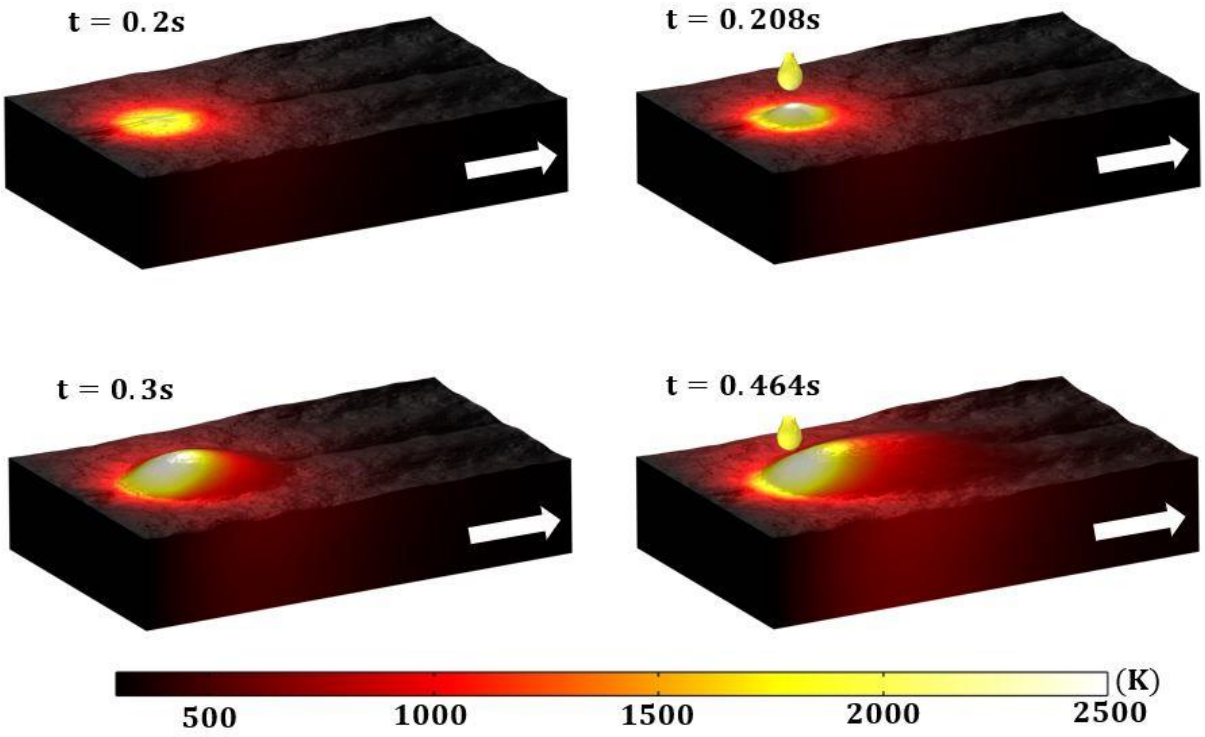

Figure 3: 3D views of the melt pool and the material deposition temperature. The snapshots show the quasi-steady state condition of the melt pools

For validation purpose, Fig. 4 and Fig. 5 show a comparison between the predicted melt pool dimensions form the numerical model and the measurements from macrograph. The comparison concerns the first layer. The predicted melt pool height is 0.82 mm while the measured one is 0.8 mm. The predicted melt pool length is 1.7 mm while the measured one is 1.89 mm. The predictions and the measurements are in good agreement even if the predicted length is slightly underestimated. But when it comes to the deposit width a noticeable discrepancy between the predictions and the measurements is observed. The model overestimates the deposit width as the predicted width is 2.7 mm while the measured one is 2.13 mm. The differences between the predictions and the measurements could come from the uncertainty on model data like thermophysical properties, of which there are many, and numerical diffusion. Despite these differences, the simulation results are found to be generally consistent with the experimental results. It is important to note that the actual length of the tracks produced in the experiments was 58 mm, whereas in the simulations, the length was limited to 8 mm in order to save computational time.

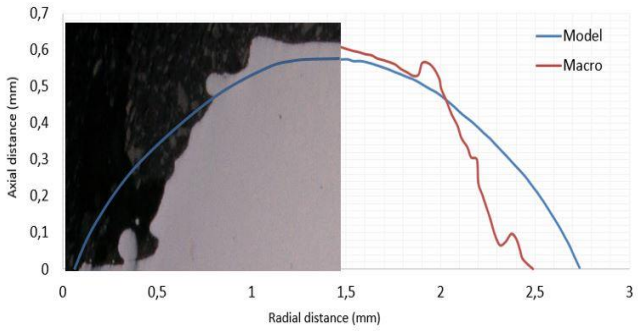

Figure 4: Macrograph – cross-section of the first layer

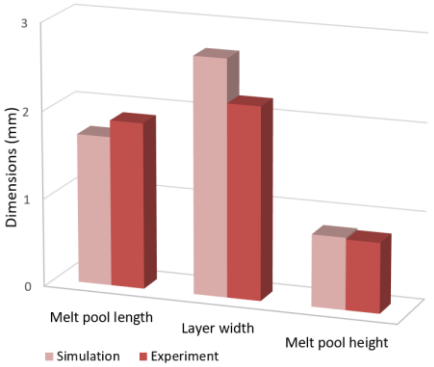

Figure 5: Comparison of the melt pool dimensions obtained by model and experiment.

5 CONCLUSION

In this study, a simplified multi-physics numerical model of the LMD process has been developed. The 3D model incorporates all the main driving physical phenomena, including heat transfer and fluid flow in the gas and the melt pool. The model is developed based on FEM in the commercial software package, COMSOL Multiphysics. The material addition and the track growth are simulated using droplet generation. The level set method is used to handle the interface tracking and the strong topological changes during the LMD process.

The model was validated against experimental results and was found to provide predictions in good agreement with measurements in terms of melt pool dimensions. However, improvements are possible and more comprehensive experimental data could help refine model assumptions.

Despite some limitations, the model provides a valuable tool for investigating the LMD process and future work will consider combining it with a simplified model at the scale of the workpiece to enhance its accuracy and computational efficiency.

REFERENCES

[1] E. Ferreira *et al.*, "Numerical and experimental investigation of gas powder flow from coaxial nozzles in Laser Metal Deposition".

[2] S. Y. Wen, Y. C. Shin, J. Y. Murthy, and P. E. Sojka, "Modeling of coaxial powder flow for the laser direct deposition process," *Int J Heat Mass Transf*, vol. 52, no. 25–26, pp. 5867–5877, Dec. 2009, doi: 10.1016/J.IJHEATMASSTRANSFER.2009.07.018.

[3] A. Fathi, E. Toyserkani, … A. K.-J. of P. D., and undefined 2006, "Prediction of melt pool depth and dilution in laser powder deposition," *iopscience.iop.org*, Accessed: Apr. 15, 2022. [Online]. Available: https://iopscience.iop.org/article/10.1088/0022-3727/39/12/022/meta?casa_token=g_xUQTFAv_UAAAAA:pbt20297KTGUDtHKRF8DSzRBPaDIPUgeTqeT6iCGLIlAJ8lN9tbeEpm-n8iDajVfrKfDAUgwoVysskM

[4] Q. Wang *et al.*, "Modelling the geometry of a moving laser melt pool and deposition track via energy and mass balances," *iopscience.iop.org*, vol. 37, pp. 1885–1895, 2004, doi: 10.1088/0022-3727/37/14/003.

[5] F. Caiazzo, V. A.- Materials, and undefined 2019, "Simulation of laser-assisted directed energy deposition of aluminum powder: prediction of geometry and temperature evolution," *mdpi.com*, 2019, doi: 10.3390/ma12132100.

[6] S. Ghosh and J. Choi, "Modeling and experimental verification of transient/residual stresses and microstructure formation in multi-layer laser aided DMD process," 2006, Accessed: Apr. 15, 2022. [Online]. Available: https://asmedigitalcollection.asme.org/heattransfer/article-abstract/128/7/662/467540

[7] R. Ye, J. Smugeresky, B. Zheng, … Y. Z.-M. S. and, and undefined 2006, "Numerical modeling of the thermal behavior during the LENS® process," *Elsevier*, Accessed: Apr. 15, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S092150930600476X

[8] "2D longitudinal modeling of heat transfer and fluid flow during multilayered - Archive ouverte HAL." https://hal.archives-ouvertes.fr/hal-00799208v1 (accessed Apr. 15, 2022).

[9] L. Han, K. M. Phatak, and F. W. Liou, "Modeling of laser deposition and repair process," *J Laser Appl*, vol. 17, no. 2, pp. 89–99, May 2005, doi: 10.2351/1.1848523.

[10] H. Qi, J. Mazumder, H. K.-J. of applied physics, and undefined 2006, "Numerical simulation of heat transfer and fluid flow in coaxial laser cladding process for direct metal deposition," *aip.scitation.org*, vol. 100, no. 2, p. 247, 2006, doi: 10.1063/1.2209807.

[11] J. Ibarra-Medina, M. Vogel, and A. J. Pinkerton, "A cfd model of laser cladding: From deposition head to melt pool dynamics," *30th International Congress on Applications of Lasers and Electro-Optics, ICALEO 2011*, pp. 378–386, 2011, doi: 10.2351/1.5062261.

[12] M. Bayat *et al.*, "On the role of the powder stream on the heat and fluid flow conditions during Directed Energy Deposition of maraging steel—Multiphysics modeling and experimental validation," *Addit Manuf*, vol. 43, Jul. 2021, doi: 10.1016/j.addma.2021.102021.