The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 17.2
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.17.2
©Civil-Comp Ltd, Edinburgh, UK, 2022

Discrete Element Method framework to simulate metallic Laser Powder-Bed Fusion additive manufacturing process

W. Leclerc[1] and A. Chams[2]

[1]Laboratoire des Technologies Innovantes UR-UPJV 3899
Université de Picardie Jules Verne, France
[2]Department of Mechanical Engineering, University of Ottawa, Canada

Abstract

The present work introduces a Discrete Element Method (DEM) framework to simulate metallic Laser Powder-Bed Fusion (L-PBF) additive manufacturing process. This latter is expected to take into account the main steps of additive manufacturing from the 3D printing G-code to the characterization of printed parts before post-processing through the simulation of laser/powder bed thermo-mechanical interaction and the determination of residual stresses and distortions. In this paper, a 3-step investigation is led to validate and exploit the developed DEM-based methodology. For validation purposes, we first consider a reference problem to compare melt pool geometrical and thermal characteristics given by Gusarov radiation model with finite element results coming from the literature. Then, we simulate the 3D printing of a simple geometric part. Finally, we exploit the developed approach to determine the influence of laser parameters in this case and more complex configurations. Results highlight the ability of DEM to reproduce L-PBF process and provide crucial information as temperature fields for optimisation purposes.

Keywords: L-PBF process, 3D printing, numerical modelling, discrete element method, Gusarov model, temperature fields

1 Introduction

This contribution deals with a DEM approach to simulate metallic L-PBF additive manufacturing process. Such a technology consists in layer-by-layer manufacturing a 3D object using a pre-defined slicing of an STL file describing its geometry. Typically, the powder bed is selectively fused by a laser beam according to an input scanning path and the process is repeated for each layer of raw materials with targeted thickness until completion. L-PBF process allows to produce metallic parts with complex inner and/or outer geometry which can not be obtained using traditional processes. Numerical modelling is of real interest to understand defects generation mechanism and set up optimised solutions to improve the quality of produced parts as function of input parameters as scanning speed, layer thickness, hatch spacing, laser power and so on.

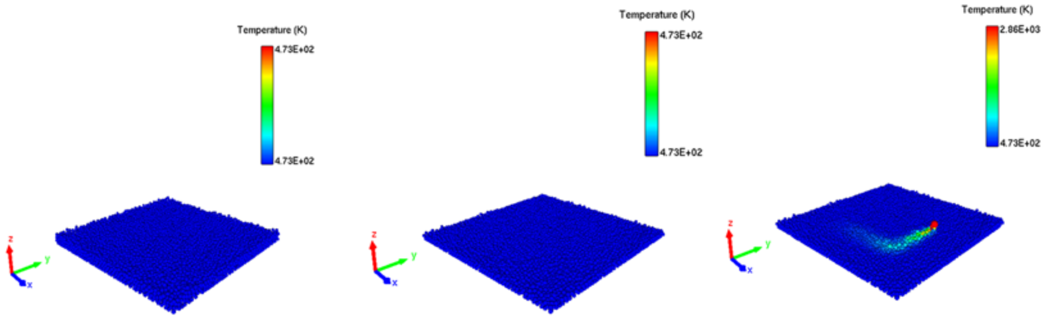
In the literature, some studies have taken benefit of Finite Element Method (FEM) to simulate L-PBF process. Two approaches can be distinguished according to the scale of modelling, namely the powder layer or the part scale. Thus, several works focused on the thermomechanical interaction between the laser beam and the melt pool [1,2]. Other contributions considered continuous multiscale models to predict part distortion and thermal induced residual stresses at the end of the process [3,4]. Nevertheless, recent pioneering works [5,6] proposed a fully DEM framework to simulate L-PBF process, and more specifically the process based on Selective Laser Sintering (SLS). These contributions highlighted the potential of DEM to model several steps of L-PBF additive manufacturing process from the powder deposition and the generation of a 3D printer G-code to the characterization of printed parts before post-processing through the simulation of laser/powder bed thermo-mechanical interaction and the determination of residual stresses and distortions. Indeed, DEM turns out to be a very flexible numerical approach which allows for a twofold description of the state of matter: particulate and consolidated in a multiscale and multiphysics framework [7,8].

2 Methods

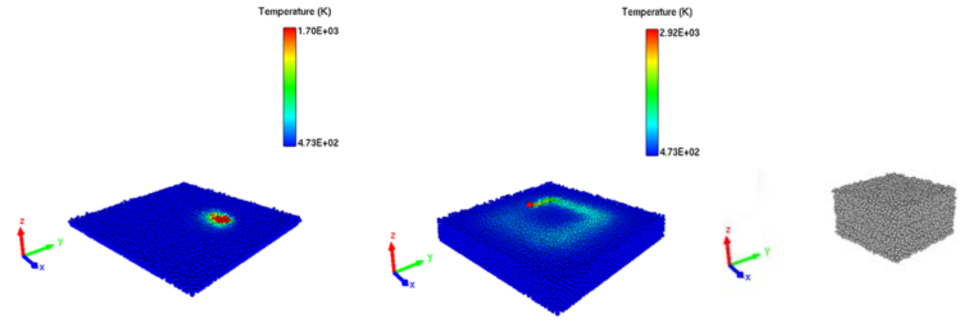
In the present work, we aim at developing and validating a 3D DEM framework to simulate L-PBF additive manufacturing process. We consider the following approach (see Figure 1) :

1. The powder deposition is modelled by simulating a layer-by-layer sedimentation process of spherical particles. Such a methodology ensures the generation of a dense and random particulate system for each powder layer. Note that particle size distribution is defined with respect to the real granulometry.
2. The powder scraping is simulated by removing all particles the centroids of which are located above the threshold defined by the thickness layer.

3. The laser displacement is reproduced according to a G-code file and a pre-established scanning strategy. During the movement, laser/powder bed interaction is simulated using an external heat source introduced in the explicit resolution of the classical heat equation at the elementary contact scale. Note that the phase change is modelled using the apparent heat capacity model, and the thermal conduction through the particulate system and the consolidated material is taken into account using the approach proposed by Haddad et al. [8].
4. The laser source is removed from the system and the cooling step is modelled considering a final pre-set temperature of 473K.
5. The additive manufacturing cycle defined by steps 1 to 4 is repeated until the completion of the 3D printed part.
6. The consolidated part is finally extracted from the particulate system and residual stresses and mechanical properties are finally determined at the end of the process.



(a) Layer deposition (b) Powder scraping (c) Laser displacement



(d) System cooling (e) 3D printing of a new layer (f) Extraction of a solid part

Figure 1 : Main steps of the simulation of the 3D printing of a simple geometrical part

3 Results

A 3-step investigation is carried out to validate and exploit the developed DEM-based methodology. For validation purposes, we first consider a reference problem to compare melt pool geometrical and thermal characteristics given by Gusarov model with finite element results coming from the literature. The studied configuration is a parallelepipedic sample of size 0.6mm×0.3mm×0.2mm composed of a thin layer of metallic powder on a solid substrate. A laser beam of power 45W and spot size 0.06mm is forced to move unidirectionnally with a velocity of 0.12m/s between x=0 and x=0.5mm. Figure 2 illustrates the temperature field at the surface of the sample at the end of the process. The initial temperature is 303K and adiabatic boundary conditions are imposed on all surfaces excepted for the extremity x=0.6mm where a temperature of 303K is set.

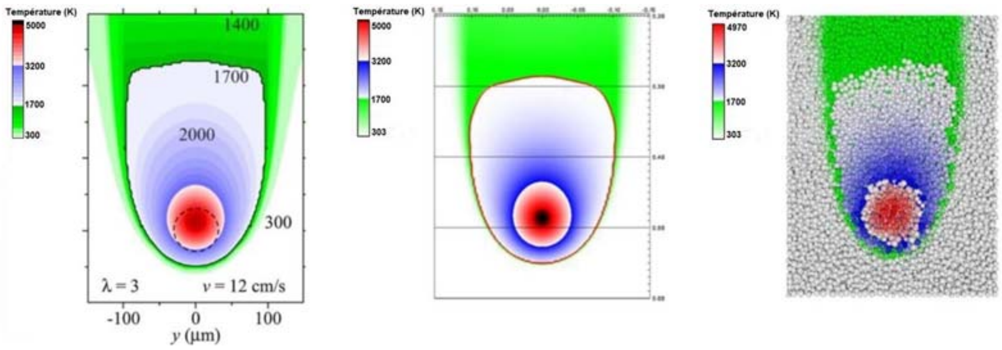


Figure 2 : Temperature fields at the surface of the sample given by (a) Gusarov model (FEM) [1] (b) Hodge model (FEM) [2] and (c) present investigations (DEM/4500 particles)

Results exhibit a good agreement between FEM and DEM results with close melt pool lengths and widths and a maximum temperature near 5000K in each case. Note that DEM produces a non-symmetrical melt pool with local disruptions related to the random particulate system. Then, the 3D printing of a simple geometrical part is simulated based on the works of Xin et al. [6]. The printed domain consists of a cubic pattern of dimensions 1mm×1mm×0.6mm which is sliced into 6 layers of thickness 0.1mm. The simulation of L-PBF process lies on the methodology described in the “Methods” paragraph. The displacement of a laser of power 200W and beam spot size 0.54mm is defined according to a G-code file and a specific scanning strategy. All physical and geometrical parameters are extracted from Xin et al’s works [6].

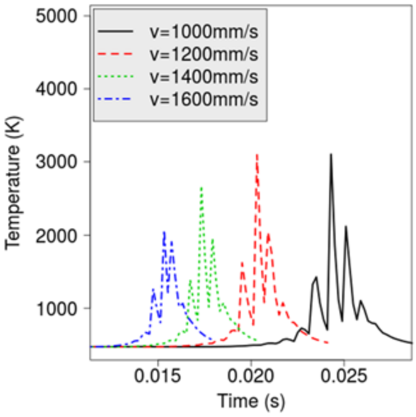


Figure 3 : Evolution of the maximum temperature as function of the laser velocity

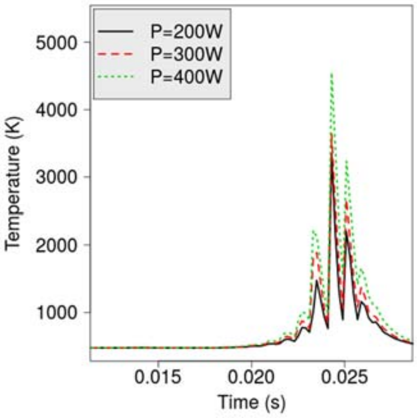


Figure 4 : Evolution of the maximum temperature as function of the laser power

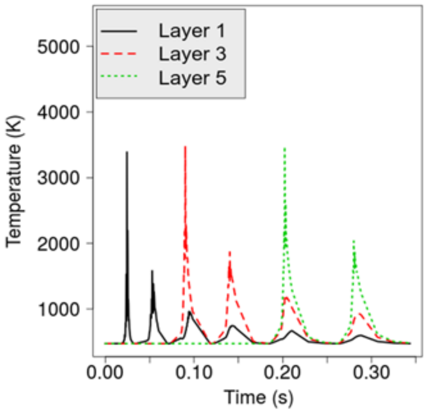


Figure 5 : Evolution of the temperature at central point of layers 1, 3 and 5

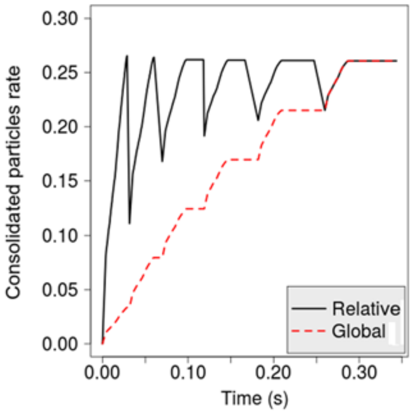


Figure 6 : Evolution of the rate of consolidated particles over the time

Figure 3 illustrates the evolution of the temperature at central point of different layers. It progressively decreases from 3346K to 598K between the first and last scanning with 6 characteristic peaks. Figure 4 shows the evolution of the rate of consolidated particles with respect to the relative and global number of deposited particles. The rate tends to a value of 0.261 which is close to the theroretical value of 0.25. The small difference is related to the consolidation of particles outside the printed domain close to the scanning path. Finally, the developed approach is exploited to evaluate the influence of laser parameters (laser velocity and power). Figures 5 and 6 exhibit that, as expected, the temperature tends to increase for a higher laser power and a slower velocity.

4 Conclusions and Contributions

Previous studies highlighted the relevance and the potential of the proposed DEM framework to model several steps of L-PBF process. In a first step, this model was compared to existing approaches based on FEM in the context of a reference problem coming from the literature. Results exhibited a quite good agreement between DEM and FEM but typical disruptions were observed in the case of the discrete method due to the randomness of the particulate system. In a second step, the influence of laser parameters as the laser beam power and its velocity was studied through the simulation of the 3D printing of a simple geometrical part composed of 6 layers. Numerical results showed that the maximum temperature is increased when the laser power is higher and the velocity is lower what is in accordance with generally accepted standards.

In a next future, we aim at extending the DEM framework to simulate the mechanical behaviour of the printed part and estimate residual stresses at the end of the process. We also expect to develop a specific DEM-SPH coupling to take into account complex fluid phenomena as Marangoni and keyhole effects which occur in the melt pool during the phase change.

References

[1] A.V. Gusarov, I. Yadroitsev, P. Bertrand, I. Smurov. Model of radiation and heat transfer in laser-powder interaction zone at selective laser melting, Journal of Heat Transfer, 072101(131), 2009.

[2] N.E. Hodge, R.M. Ferencz , J.M. Solberg. Implementation of a thermomechanical model for the simulation, Computational Mechanics, 33-51(54), 2014.

[3] H. Peng, M. Ghasri-Khouzani, S. Gong, R. Attardo, P. Ostiguy, R.B. Rogge et al. Fast prediction of thermal distortion in metal powder bed fusion additive manufacturing: Part 2, a quasi-static thermo-mechanical model, Additive Manufacturing, 869-882(22), 2018.

[4] D. Moser, M. Cullinan, J. Murthy. Multi-scale computational modeling of residual stress in selective laser melting with uncertainty quantification, Additive Manufacturing, 100770(29), 2019.

[5] J.C. Steuben, A.P. Iliopoulos, J.G. Michopoulos. Discrete element modeling of particle-based additive manufacturing processes, Computer Methods in Applied Mechanics and Engineering, 537-561(305), 2005.

[6] H. Xin, W. Sun, J. Fish. Discrete element simulations of powder-bed sintering-based additive manufacturing,International Journal of Mechanical Sciences, 373-392(149), 2018.

[7] W. Leclerc Discrete Element Method to simulate the elastic behavior of 3D heterogeneous continuous media, International Journal of Solids and Structures, 86-102(121), 2017.

[8] H. Haddad, W. Leclerc, G. Alhajj Hassan, A. Ammar, C. Pélegris, M. Guessasma, E. Bellenger. Numerical investigation of heat conduction in heterogeneous media with a discrete element method approach, International Journal of Thermal Sciences, 106799(164), 2021.