COMPUTATIONAL MODELING OF THE INERT GAS FLOW BEHAVIOR ON SPATTER DISTRIBUTION IN SELECTIVE LASER MELTING

Xiaobing Zhang^{1,2}, Charles Tuffile², Bo Cheng^{2,*}

¹Department of Mechanical and Aerospace Engineering Rutgers, The State University of New Jersey Piscataway, NJ, 08854, USA
²Robert Bosch LLC, Cambridge, MA, 02139, USA
*Corresponding author: Bo.Cheng@us.bosch.com

Abstract

In the selective laser melting (SLM) process, the spatter, introduced by moving melt pools, can contaminate the build region and potentially reduce the part quality. A well-designed inert gas flow system can help to effectively remove the process emissions. Therefore, it is critical to understand the flow characteristics as well as the interactions between gas flow and spatter. In this study, a Computational Fluid Dynamics (CFD) model for the SLM gas flow system has been developed to simulate the complicated flow behavior in the chamber. The generation of spatter over the build region has been simulated by a discrete phase model (DPM). The Eulerian-Lagrangian modeling technique has been applied to accurately capture the influence of gas flow on ejected spatter. The process variables that can significant affect the gas flow efficiency in the chamber, such as inlet design, volume flow rate and material property, have been numerically investigated.

Keywords: Selective Laser Melting (SLM); Computational Fluid Dynamics (CFD); Discrete phase method (DPM); Gas flow; Spatter

1. Introduction

In selective laser melting (SLM) process, a high-energy laser beam is utilized to melt and fuse the metallic powder materials. The accompanied high local temperature can easily exceed the material evaporation point and cause evaporation. The complicated vaporization effect may cause a "vapor-jet" effect, leading to the generation of emissions. The emissions include the vaporization gases, "vapor jet" entrained powders, and liquid droplets ejected from melt pool due to melt pool dynamics. Therefore, the spatter (ejected particles from or around melt pool) mainly consists of droplet spatter and powder spatter [1]. Numerical Modeling has been utilized to understand the complex process physics in powder bed additive manufacturing process. Lee and Zhang [2] developed a discrete element method (DEM) model to simulate the powder spreading process in SLM. In addition, a computational fluid dynamics (CFD) model is developed to investigate the melt pool dynamics with the incorporation of DEM generated powder bed. The thermal information was utilized to calculate solidification morphology and grain size. Panwisawas et al [3] simulated the positions of powder particles in a powder bed by dropping spheres based on encountered obstacles. Micro-scale CFD simulations were performed to establish the relationship between laser process parameters, melt pool and microstructure. Shrestha and Chou [4] modeled the two-layer powder deposition process in SLM, their simulation showed interlayer lack-of-fusion

phenomenon if a high laser scanning speed was applied. Using both DEM and CFD modeling tool, Cheng et al [5] studied the powder spreading condition on melt pool characteristics in SLM process. A higher powder bed packing density, caused by smaller roller rotational speed, lead to smaller re-melting depth. Cheng et al [6] also investigated the evolution of porosity in a single track scanning process. Pores could be formed by the collapse of keyhole. Lawrence Livermore National Laboratory (LLNL) utilized the arbitrary lagrangian-eulerian (ALE) package to study various physical processes such as melt pool dynamics, scanning track surface morphology, and melt pool emission [7, 8, 9, 10]. A comprehensive review of additive manufacturing process thermal analysis and simulation can be found in literature [11]. However, it is very difficult to simulate the spatter motion over the entire build chamber using the micro-scale melt pool model.

On the other hand, spatter characteristics can be studied by experimental measurement. Using the high-speed X-ray imaging technology, Zhao et al [12] were able to obtained important spatter parameters such as spatter count, diameter, and velocity with respect to different scanning speeds and laser powers. Their observation indicated that more and larger speed spatters could be generated from higher laser power condition. Gunenthiram et al [13] also experimentally analyzed the formation of spatters in SLM process. By introducing a high speed imager in SLM system, they quantified the spatter ejections as well as possible correlation with melt pool dynamics. Their results showed that larger sized spatters could be generated for SS316L material if high laser volume energy density was applied on powder bed. On the other hand, the droplet might be incorporated into melt pool area for Al-12Si material, thus higher spattering was observed on SS316L powder bed.

Without any removal process, the spatters may re-deposit on the powder bed due to gravity and contaminate the build area, potentially affecting the build part quality. In common practice, a shielding gas flow can help to remove the ejected particles, as shown in Figure 1. However, the spatter removal efficiency heavily depends on the design and optimization of the gas flow system in the build chamber. Studies about the gas flow system are sparsely found in the literature. Philo et al [14,15] developed a CFD model to study the gas flow characteristics inside the Renishaw AM250 build chamber. The movement of spatters was simulated by discrete phase method (DPM). The simulated velocity field in the chamber was validated against the flow field obtained by Hot Wire Anemometer (HWA) measurement. They found that the flow uniformity and average flow velocity could be influenced by inlet rail radius and inlet/outlet height. Chen et al [16] implemented a CFD tool to optimize the gas flow inside Renishaw AM250 chamber. A secondary downward flow from the to chamber, besides the main horizontal inlet flow, was critical to avoid the recirculation of gas flow inside build chamber. Wang and Chang [17] tried to optimize the flow uniformity inside a selective laser sintering (SLS) system. A CFD model was utilized to investigate the effect of influential factors on flow velocity profile and uniformity, e.g., the trapezoid push nozzle, the suction tunnel and nozzle-to-plane distance. However, optimal design and modeling for build chamber to increase spatter removal rate, especially considering gas flow - spatter interaction, is still not thoroughly investigated.



Figure 1. Graphic description of problem.

This study developed a comprehensive fluid-particle interaction CFD model to simulate the gas flow effect on spatter distribution. The spatter motion trajectory is studied to better understand the particle dynamics inside the gas flow chamber. Several influential process and design parameters of the gas flow system, such as flow rate, inlet height and width, as well as material density, have been investigated to enhance the removability of the process emissions.

2. Numerical Methodology

In this study, the objective is to maximize the removal efficiency of process emissions during the SLM process. Therefore, the design of the gas flow system, including gas inlet width, inlet height, volume flow rate, and processing materials, will be thoroughly investigated. A generic baseline SLM build chamber design (Renishaw AM250) is shown in Figure 2 (a). The commercial simulation package, ANSYS Fluent, was used to build a gas-spatter interaction model. A CFD fluid flow model was used to describe the gas flow characteristics inside build chamber. The fluid flow is assumed to be steady, incompressible and turbulent flow. Standard Navier-Stokes equations and k-e turbulent model are used to describe the fluid characteristics [14,15].

In addition, a Discrete Phase Method (DPM) model was developed to study the spatter distribution within the SLM chamber. Spatters are generated by DPM method and fully coupled with the gas phase. To efficiently model the gas-spatter interaction inside the chamber, several assumptions have been made:

(1) Instead of generating the spatters from the melt pool level, the spatter source are modeled as five lines evenly distributed on the powder bed to cover the entire build area, as shown in Figure 2 (a).

(2) The spatter particles are ejected with three different ejection angles to the horizontal substrate: 60° , 90° , and 120° .

(3) All the ejection sources have Gaussian distributed particles ranging from diameter 20 μ m to 80 μ m with an ejecting speed of 3 m/s.

(4) The spatter material is SS316L with a density of 7950 kg/m^3 .

Different boundary conditions have been applied to different domains of the model. To calculate the spatter-chamber wall surface contact, "Wall" boundary condition with DPM settings are used. The DPM particles will be rebounded off from the "reflect" wall boundaries with a

modified momentum. The trajectory calculations are terminated and recorded as "trapped" if the particles fall on "trap" wall boundaries. In this simulation, only the powder bed surfaces, including the five spatter source lines, are listed as DPM "trap" boundary conditions. Other chamber wall surfaces are marked as "reflect" boundaries. The inert gas firstly enters the inlet rail with given flow rate, then flows into the main build chamber through a row of cylindrical nozzles with 12 mm in diameter. The gas and spatter flow out of the domain through outlet. Therefore, the gas inlet is set to be "mass flow rate" while "outflow" boundary condition is applied for the outlet. The inert gas used in the simulation is argon with a viscosity of 0.00002125 kg/m-s and a density of 1.6228 kg/m³. The mass flow rate is set as 0.00677 kg/s (250 L/min).

The entire domain was meshed using Tetrahedron elements. To capture flow characteristics at boundary layer, 8 inflation layers were added upon the substrate. Figure 2 (b) shows the model mesh information, the model has \sim 1.5 million elements. For all simulated cases in this study, there may be small variations in the total amount of element which is caused by the slight change of gas chamber geometry.



(b) Mesh used for computational domain Figure 2. Model geometry and mesh information.

To solve the coupled fluid-particle momentum and pressure equations, the SIMPLE (Semi-Implicit Method for Pressure Linked Equations) solution method was used. The solution was considered to be converged when the residuals of continuity and momentum were smaller than 1×10^{-4} . High-performance computing (HPC) system is utilized to conduct simulations. The specification of the computing node is: $2 \times$ Intel Haswell E5-2680v3 (24 cores per node) and 64 GB RAM. It takes ~2 hours to obtain converged results using two nodes.

3. Results and Discussion

In this part, one baseline design simulation is used to show the gas flow variations and particle behaviors. Afterwards, three different design parameters, inlet width, inlet height and flow rate, are adjusted to show their influence on the system and spatter removal. Finally, different spatter material, namely, AlSi10Mg, Ti64 and SS316L, have been simulated to study the particle density effect. To quantify emission removal performance, a "clear rate" is used to describe the spatter removal efficiency. The clear rate is defined as the ratio of the number of spatter particles removed out of the build region (powder bed) to the total number of spatters.

3.1 Overview of the baseline model

Figure 3 shows the simulation results for gas-spatter interaction in the baseline design chamber. The spatters firstly ejected to the gas chamber from the build region, then the incoming gas flow blew the particles toward the outlet. However, not all spatters can be removed from the build chamber, they may re-deposited to the chamber substrate due to gravity.



Figure 3. Typical simulation results.

Two perspectives of the velocity contours inside the system are discussed below. Figure 4 (a) is a side view of the chamber gas flow velocity contours located in the middle of the chamber. It is seen that high gas velocity streams come out of the inlet nozzles and flow down toward the substrate. The spatter trajectories are affected by the gas flow and spatters move toward the outlet, as shown in Figure 4 (b). It is seen that the spatter generated in the region closest to the outlet are mostly removed. Figure 4 (c) is a top view of the gas flow velocity contours on the center-plane (center of inlet nozzle), where a high velocity concentration region is observed around the inlet region with a near triangular shape. The spatter distribution map shows that the substrate region close to inlet has little spatter concentration while the region close to outlet has high spatter concentration, as shown in Figure 4 (d). The spatter re-deposition map generally follow the velocity contour: high velocity region has little re-deposition phenomenon. With the decrease of the inlet gas flow velocity, the spatters fall down to substrate region that is away from the inlet region. The overall clear rate of the baseline design is 60.4%.



(b) Sample spatter trajectory - Side view(d) Spatter distribution on substrate Figure 4. Velocity contours and spatter distribution of the baseline chamber design.

3.2 Inlet flow rate effect

The movement of the spatter is largely decided by gas flow and particle condition. Therefore, a strong inlet gas flow may help to improve spatter clear rate. Three different inlet flow rates, 0 L/min, 250 L/min and 500 L/min, were tested to investigate flow rate effect on spatter distribution. A flow rate of 0 L/min means no gas flow is applied. The spatters simply eject outward then fall back under the gravity force. The drag force imposed on the particles is little due to the negligible gas flow rate. With the increase of flow rates, the gas flow starts to affect the particle motion and the spatter trajectory changes significantly, e.g., the spatters hardly reach outlet for 0 L/min case while majority of the spatters can flow through the outlet for 500 L/min case, as shown in Figure 5. The clear rate for the three cases are: 0%, 60.4%, 81.1% for 0 L/min, 250 L/min, and 500 L/min respectively. Therefore, high flow rate is helpful for spatter removal.



(a) 0 L/min	(b) 250 L/r	nin	(c) 500 L/min
Figure 5. Spatter	e-deposition maps and tra	ajectories with	different flow rates.

3.3 Inlet width effect

The inlet width has been varied proportionally to study the inlet width effect, all other parameters are kept unchanged as the baseline case, e.g., a flow rate of 250 L/min is used. The nozzle to nozzle distance has been adjusted accordingly. The effects of three inlet widths of 225 mm, 250 mm and 275 mm have been compared, as is shown in Figure 6. The flow field differences between different inlet width cases are subtle. In all cases, the flow velocity is stronger in the middle of the chamber, but this effect is particularly noticeable for a smaller inlet width. Larger inlet widths such as 275 mm, results in a lower gas flow velocity above the build area which diminishes the particle removal efficiency. An inlet width with same or similar width as the build region (powder bed) width of 250 mm is shown to be most effective, as the highest particle clear rate of 60.4% with the inlet width of 250 mm, compared to the rate of 60.0% for a narrower width of 225 mm and 59.3% for a wider width of 275 mm.



3.4 Inlet height effect

The inlet height effect on spatter re-distribution is also investigated. Inlet height is defined as the distance from the center plane of inlet nozzles to the substrate plane. Three designs with different inlet heights: 50 mm, 67.5 mm and 85 mm are compared in this section while all other parameters are the same as the baseline case. Figure 7 shows the re-deposition maps and velocity contours at center vertical plane. It is found that the case with inlet height equal to 67.5 mm (Figure 7 (b)) removes the most particle emissions (60.4% clear rate). Lower inlet height design (Figure 7 (a)) has a clear rate of 59.8%, and higher inlet height design (Figure 7 (c)) has a clear rate of 57.7%. It demonstrates that a moderate inlet height is preferred to remove the most particles. It is observed that the high gas velocity region moves up and down along with the inlet height modifications. The spatters have pre-defined initial ejection velocities, and it falls after reaching a peak height due to gravity. Therefore, spatters may penetrate the high velocity region with a low inlet height

design. On the other hand, the high gas velocity region may be too high to exhibit influence on the spatter particles for a high inlet height design case.



3.5 Spatter material property effect

To examine the effects of the spatter material property, three materials are chosen and compared using the baseline case. The three common SLM materials are AlSi10Mg, Ti64, and SS316L. The corresponding densities are about 2700 kg/m³, 4400 kg/m³ and 7950 kg/m³. Even though the interactions between the particle and gas fluid are considered in the simulations, the influence of the particle on the gas fluid field is minor such that the velocity fields remain almost the same for these three cases. Figure 8 shows the spatter particle trajectories of the three materials. It is shown that the spatter material is also a significant factor for the system design. The particle trajectory with lighter material shows higher similarity to the gas flow velocity field. This can be explained that the ratio between the flow drag force and the gravity will be larger for a lower density spatter material, therefore, the individual particle motion is dominated by fluid drag force. The resulted clear rate is higher for lighter materials, e.g., 69.4% for AlSi10Mg, 68.3% for Ti64 and 60.4% for SS316L.



(a) AlSi10Mg (b) Ti64 (c) SS316. Figure 8. Spatter re-deposition maps and trajectories with different processing materials.

4. Conclusion

In this study, a fully coupled CFD-DPM model has been developed to investigate the gas flow effect on spatter distribution inside the SLM build chamber. The fluid flow characteristics have been calculated by a steady-state and turbulent CFD model. In addition, the spatter generation is modeled by DPM model. The influence of different build chamber parameters, such as inlet flow rate, inlet width and height, and spatter materials, have been studied. The major findings can be summarized as follows:

(1) The flow rate has considerable effect on the spatter particle removing process. It is observed that a higher flow rate can significantly affect the spatter moving trajectory toward the outlet, which can contribute to obtain a higher clear rate, e.g., a clear rate of 81.1% for a flow rate 500 L/min while it is 60.4% for a flow rate of 250 L/min.

(2) Three inlet widths were compared using the developed model. It is found that the inlet width has minor effects on the clear rate. An inlet width that is similar to the width of the build area (powder bed region) shows best performance for clear rate.

(3) The effect of inlet height has been investigated as well. Spatters may penetrate the high velocity region (low inlet height design), or the high gas velocity region may be too high to blow away spatters (high inlet height design). A moderate height is preferable for spatter removals.

(4) The spatter materials have a noticeable effect on particle motion trajectory and clear rate. A higher similarity to the gas flow velocity stream field is shown for the trajectory of lighter spatters. It is because the spatter motion is dominated by fluid drag force for low density spatter. Therefore, higher clear rate is expected for lighter spatters, e.g., clear rate is 69.4% for AlSi10Mg while it is 60.4% for SS316L.

The future work of this study will be focused on comprehensive validation of the developed model. The simulated flow field will be compared with experimental measurement. In addition, the spatter source will be updated with actual particle size distribution, ejection speed and angle to further improve the simulation accuracy.

5. Reference

[1] Yang Liu, Yongqiang Yang, Shuzhen Mai, Di Wang, and Changhui Song. "Investigation into spatter behavior during selective laser melting of AISI 316L stainless steel powder." Materials & Design 87 (2015): 797-806.

[2] Y. S. Lee, W. Zhang. "Modeling of heat transfer, fluid flow and solidification microstructure of nickel-base superalloy fabricated by laser powder bed fusion." Additive Manufacturing 12 (2016): 178-188.

[3] Chinnapat Panwisawas, Chunlei Qiu, Magnus J. Anderson, Yogesh Sovani, Richard P. Turner, Moataz M. Attallah, Jeffery W. Brooks, and Hector C. Basoalto. "Mesoscale modelling of

selective laser melting: Thermal fluid dynamics and microstructural evolution." Computational Materials Science 126 (2017): 479-490.

[4] Subin Shrestha, Kevin Chou. "Computational Analysis of Thermo-Fluid Dynamics with Metallic Powder in SLM." In TMS Annual Meeting & Exhibition, pp. 85-95. Springer, Cham, 2018.

[5] Bo Cheng, Xiaobai Li, Charles Tuffile, Alexander Ilin, Hannes Willeck, and Udo Hartel. "Multi-physics modeling of single track scanning in selective laser melting: powder compaction effect." In 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, Austin, TX, USA, August 13-15, 2018, pp. 1887-1902.

[6] Bo Cheng, Charles Tuffile. "Numerical study of porosity formation with implementation of laser multiple reflection in selective laser melting." ASME 2019 14th International Manufacturing Science and Engineering Conference, June 10-14, 2019, Erie, PA, USA, MSEC2019-2891.

[7] Saad A. Khairallah, Andy Anderson. "Mesoscopic simulation model of selective laser melting of stainless steel powder." Journal of Materials Processing Technology 214, no. 11 (2014): 2627-2636.

[8] Saad A. Khairallah, Andrew T. Anderson, Alexander Rubenchik, and Wayne E. King. "Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones." Acta Materialia 108 (2016): 36-45.

[9] Manyalibo J. Matthews, Gabe Guss, Saad A. Khairallah, Alexander M. Rubenchik, Philip J. Depond, and Wayne E. King. "Denudation of metal powder layers in laser powder bed fusion processes." Acta Materialia 114 (2016): 33-42.

[10] Sonny Ly, Alexander M. Rubenchik, Saad A. Khairallah, Gabe Guss, and Manyalibo J. Matthews. "Metal vapor micro-jet controls material redistribution in laser powder bed fusion additive manufacturing." Scientific reports 7, no. 1 (2017): 4085.

[11] Zhaorui Yan, Weiwei Liu, Zijue Tang, Xuyang Liu, Nan Zhang, Mingzheng Li, and Hongchao Zhang. "Review on thermal analysis in laser-based additive manufacturing." Optics & Laser Technology 106 (2018): 427-441.

[12] Cang Zhao, Kamel Fezzaa, Ross W. Cunningham, Haidan Wen, Francesco De Carlo, Lianyi Chen, Anthony D. Rollett, and Tao Sun. "Real-time monitoring of laser powder bed fusion process using high-speed X-ray imaging and diffraction." Scientific reports 7, no. 1 (2017): 3602.

[13] V. Gunenthiram, P. Peyre, Matthieu Schneider, Morgan Dal, Frédéric Coste, Imade Koutiri, and Rémy Fabbro. "Experimental analysis of spatter generation and melt-pool behavior during the powder bed laser beam melting process." Journal of Materials Processing Technology 251 (2018): 376-386.

[14] A.M. Philo, C.J. Sutcliffe, S. Sillars, J. Sienz, S. G. R. Brown, and N. P. Lavery. "A study into the effects of gas flow inlet design of the Renishaw AM250 laser powder bed fusion machine using computational modelling." 28th Annual International Solid Freeform Fabrication Symposium-An Additive Manufacturing Conference, Austin, TX, USA, August 7-9, 2017, pp.1203-1219.

[15] A. M. Philo, D. Butcher, Stuart Sillars, C. J. Sutcliffe, J. Sienz, S. G. R. Brown, and N. P. Lavery. "A Multiphase CFD Model for the Prediction of Particulate Accumulation in a Laser Powder Bed Fusion Process." In TMS Annual Meeting & Exhibition, pp. 65-76. Springer, Cham, 2018.

[16] Yu Chen, Guglielmo Vastola, and Yong Wei Zhang. "Optimization of Inert Gas Flow inside Laser Powder-Bed Fusion Chamber with Computational Fluid Dynamics." In 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, Austin, TX, USA, August 13-15, 2018, pp. 1931-1939.

[17] Wei-Cheng Wang and Chia-Yao Chang. "Flow analysis of the laminated manufacturing system with laser sintering of metal powder. Part I: flow uniformity inside the working chamber." The International Journal of Advanced Manufacturing Technology 92.1-4 (2017): 1299-1314.