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Spatter transport by inert gas flow in Selective Laser Melting: A simulation study

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Abstract

Spattering is an unavoidable phenomenon during Selective Laser Melting (SLM). The distinctively large and dark solidified molten particles have always been observed on the powder bed, leading to the potential deterioration of the final printed parts. In commercial SLM machines, inert gas flow is pumped into the chamber over the powder bed to remove spatter and other unwanted by-products such as metal vapour and plasma plumes. However, traces of spatter still remain on the powder bed and the regions close to the chamber outlet. In this work, the trajectories of spatter particles were tracked using the Discrete Phase Model (DPM). The continuous fluid domain was solved using three-dimensional Computational Fluid Dynamics (CFD) simulations. The entrainment effects on the hot ejections as well as the recoil pressure driven ejections were considered. In other words, it was assumed that the latter were also entrained by the metal vapour and laser plume. The final distribution characteristics downstream of the cross-flow ($-x$ direction) were validated by an earlier experimental study. The results show that a gradually decreasing trend in terms of the spatter size and mass distributions were obtained from the simulations which showed good

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agreement with the earlier experiments. It was also shown that the trajectories of the spatter particles were governed mainly by their initial momentum when the inert gas flow velocity was increased. While complete removal of the spatter particles from the powder bed was not achieved, the presence of the inert gas flow aided in the transport of a majority of the particles further downstream giving a more even mass distribution. Also, in spite of not accounting for the complete multi-physics of the SLM process and the associated recoil pressure driven ejections, the proposed spatter transport simulations can be applied in future gas cross-flow optimisation designs for the effective removal of spatter over the powder bed in commercial SLM machines.

Keywords: Additive Manufacturing, Selective Laser Melting, Inert Gas Flow, Spatter Distribution, Computational Fluid Dynamics, Discrete Phase Model

1. Introduction

In laser-based manufacturing processes, spattering refers to the ejection of molten material from the melt pool, followed by solidification and then possible deposition onto nearby regions. With respect to Selective Laser Melting (SLM), initial work on this phenomenon by Qiu et al. [1] using high speed imaging and modelling revealed that the Marangoni effects in the melt pool coupled with the recoil pressure exerted by the metal vapour expansion were mainly responsible for the ejection of molten material. Another study by Khairallah et al. [2] who introduced a three-dimensional high fidelity power-scale model, showed how the melt pool dynamics generated spattering and pores during SLM. Recoil pressure exertion onto the melt pool was once again reported as a main cause of spattering of molten metal which were initially elongated but disintegrated into smaller droplets.

However, another mechanism leading to spattering was recently brought to light. The use of high speed videos and simulations proved to be crucial

in elucidating the major and dominant cause of spattering. Bidare et al. [3] became the first to develop a finite element model for powder bed fusion which incorporated laser plume and also the inert atmosphere above the stainless steel 316L powder bed. As part of their extensive work, schlieren imaging of the interaction between the laser beam and the powder bed at varying laser power and speeds were also carried out. It was reported that at high laser power and speed, particles were ejected backwards, in the opposite direction to the laser scanning. Instead of the recoil pressure, the motion of the particles were observed to be largely induced by the plume of metal vapor and plasma above the melt pool. Their work lend support to that done by Ly et al. [4], who first proposed that the material ejection during powder bed fusion processes are mainly due to the metal vapor driven entrainment, leading to local denudation and deposition of molten droplets over the powder bed. Gunenthiram et al. [5] also reinforced the proposed particle entrainment theory by attributing the ejection of spatters to the induced gas flow caused by the metal vapor plume.

The effects of spatter particles during SLM have recently been studied. Due to their significantly larger size as compared to the fresh powder, the layer thickness would be non-uniform should the spatter particles deposit on powder bed [6]. From the energy density (Ψ) equation, $\Psi = P/(v \cdot h \cdot t)$, where P is the laser power, v is scan velocity, h is hatch space and t is layer thickness [7]. Thus a greater amount of energy would be required to completely melt the spatter particles in order to achieve a constant melt pool throughout the laser scanning. Porosity due incomplete melting were reported by Wang et al. [8], which were attributed to the presence of spatter particles embedded in between powder layers. Additionally, laser-spatter interactions have also been observed as significantly bright sparks, with the use of high-speed cameras, which could have possibly led to the reduced heat energy from the laser beams during SLM

[9]. Thus, it is crucial to effectively eliminate the spatter particles during SLM to obtain printed parts of optimal properties.

With respect to the inert gas flow within the SLM chamber, several studies have been performed. Ferrar et al. [10] showed that a more uniform flow across the powder bed resulted in printed parts with lower porosity and greater compressive strength. This is due to the increased efficiency in the removal of condensate which is present in the path of the laser, leading to beam scattering. Wang and Chang [11] analysed the flow within an SLM chamber using numerical simulations as well as hot-wire anemometry. It was found that in order to maintain inert gas flow uniformity, energy dissipation had to be minimised such that vortex formation could be delayed. This was achieved with high suction velocities at the chamber outlet. More recently, Philo et al. [12] performed Eulerian-Lagrangian simulations in ANSYS Fluent using the Discrete Phase Model (DPM) which was validated with hot-wire anemometry data of the inert gas flow velocities. Identification of recirculation zones and characterisation of spatter accumulation showed how undesirable particles get deposited within the SLM chamber. Ladewig et al. [13] reported re-depositions of process by-products in regions of low flow velocity near the gas outlet of the SLM chamber. However, the validation of the mentioned work in terms of spatter distribution on the powder bed is yet to be carried out.

A wide range of studies have been performed, where the use of CFD simulations together with the Lagrangian approach across the micro to meso and then to macro scales, as reviewed by Tenneti and Subramaniam [14]. For example, Akilli et al. [15] investigated the characteristics of particle flow in a horizontal pipe after a 90° elbow. The CFD simulations coupled with the Lagrangian method for the particles while accounting for particle-particle and particle-wall collisions, showed good agreement with the particle size distribution observed

in the experiments. To increase the efficiency of the Lagrangian method, Kloss et al. [16] proposed a technique to switch from Discrete Element Method (DEM), where particle-particle collisions are computed, to DPM in dilute regions of the fluid domain. Their method showed that there were no significant effects on the final results of the simulation.

During SLM, a host of multi-physics processes occur simultaneously; heating, melting, evaporation, solidification and also spatter ejection from the melt pool. Previous studies have attempted to elucidate the causes of the spattering either via recoil pressure or entrainment of such particles into metal vapour and plasma plumes. However, the transport of deleterious by-products which include spatter as seen in Fig. 1, is often neglected. Insights into the spatter transport by the gas flow will undoubtedly be critical during the design of such systems for commercial SLM machines, especially when the effective removal of spatter is crucial to minimise contamination over a large powder bed. For such cases, the spatter has to be transported over a further distance. Since it is significantly computationally expensive to model multi-physics processes concurrently, the main focus of this study is on the simulations of the spatter removal by the inert gas flow during SLM. A DPM approach is undertaken for the simulations of solid spatter particles in gas cross-flow. The simulation results were then validated with an earlier study on spatter mass and size distributions on the powder bed, specifically in regions A to D as labelled in Fig. 1 [17].

2. Numerical modelling

The transport of spatter particles by the inert gas flow is deemed as a gas-solid flow. Dilute flow is considered since the particle motion is generally controlled by the lift and drag forces acting on them. This is as opposed to dense flow, where the particle motion is significantly influenced by particle-particle col-

Figure 1: Schematic of spatter ejection from melt pool and its transport by the inert gas flow (green arrows) in the -x direction. Spatter distribution in regions marked A to D will be the main areas of interest in this study.

lisions such as in hoppers, fluidized beds and pneumatic transport applications. In the Eulerian-Lagrangian model, Computational Fluid Dynamics (CFD) is used for the gas flow which involves the conservation of mass and momentum while the spatter particles are modelled using the Discrete Phase Model (DPM) which involves the momentum conservation equations. With regards to CFD, the fluid domain is treated as a continuum, while DPM tracks particles through the flow field. Coupling is often adopted to account for the interaction forces between the particles and fluid. In this case, one-way coupling is used since the gas solid flow is assumed to be dilute (low volume fraction of particles) [16].

2.1. CFD

For fluid flow which are wall-bounded and have small mean pressure gradients, the turbulent $k - \varepsilon$ model is utilised. The transport equations for the turbulence kinetic energy (t) and that of the dissipation rate of ε (t), for the realizable $k - \varepsilon$ model as proposed by Shih et al. [18] and validated by Kim et al. [19], are given as

Turbulent kinetic energy transport equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon \quad (1)$$

Energy dissipation transport equation:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b \quad (2)$$

where G_k and G_b refer to the turbulence kinetic energy generation due to the mean velocity gradients and due to buoyancy respectively. μ_t is the eddy viscosity, and constants $C_{1\varepsilon} = 1.44$, $C_2 = 1.9$, $\sigma_k = 1.0$. $C_{3\varepsilon}$ refers to the degree to which ε is affected by the buoyancy of the fluid flow as studied by Henkes et al. [20]. However, the buoyancy force given by $\vec{F}_B = m_p \frac{\rho}{\rho_p} g$ in this gas-solid flow simulation can be neglected since $\rho/\rho_p \ll 1$ [21]. Lastly,

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \eta = S \frac{k}{\varepsilon}, S = \sqrt{2 S_{ij} S_{ij}} \quad (3)$$

2.2. DPM

In this study, the Discrete Phase Model (DPM) was applied where the particles are tracked throughout the flow field in a Lagrangian manner. DPM has been reported to be appropriate for modelling dilute particle-laden flow [22]. It was also implemented by Philo et al. [23] in their study of spatter removal by the shielding gas in SLM. For the case of dilute gas-solid flow with low particle volume fraction, particle-particle interactions are neglected and one-way coupling is considered. This would reduce the computational requirements of the simulations as it would be possible to inject the particles simultaneously in the domain.

In Cartesian coordinates, the force balance equation takes into account the forces acting on the particle and is given as:

$$\frac{d\vec{u}_p}{dt} = \frac{\vec{u} - \vec{u}_p}{\tau_p} + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F} \quad (4)$$

where the first term on the right hand side is the drag force per unit particle mass, followed by gravitational force and lastly additional forces such as the virtual mass, rotational, thermophoretic electrostatic or magnetic forces wherever applicable. Also, $\vec{u}_p$ is the particle velocity, d_p is the particle diameter and ρ_p is the particle density. Parameters without the subscript refers to the property of the fluid, with μ is the fluid molecular viscosity and τ_p refers to the particle relaxation time [24] and is defined as:

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_D Re} \quad (5)$$

For smooth particles, the drag coefficient C_D [25] is:

$$C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re} \quad (6)$$

where the constants a with subscripts are applied over several ranges of Re . Re is the relative Reynolds number and is given as:

$$Re \equiv \frac{\rho d_p |\vec{u}_p - \vec{u}|}{\mu} \quad (7)$$

3. Simulation set-up

The simulation set-up in this study is based on the work conducted by Philo et al. [23]. Three-dimensional simulations were performed using the commercial software, ANSYS Fluent 18.2. The computational domain was scaled to be a 1:1 model in terms of the length (x axis) and height (z axis) of the actual SLM

280 chamber seen in Fig 2a, with dimensions of 425×386 mm. In this study, the depth (y axis) was limited to 140 mm since in our previous experimental work, the region for spatter collection was set to be 40×120 mm to account for possible depositions of spatter along the y directions.

Since the spatter ejection occurs at the powder bed, it is assumed that the deactivation of the top gas inlet would have insignificant effects on the spatter transport. The main function of the gas flow originating from the top inlet is to minimise deposition of condensate and other by-products on the lens of the lasers. Thus, to reduce the computation costs, argon gas flow was only initialised at the bottom gas inlet as illustrated in Fig 2b.

(a)

(b)

Figure 2: (a) Actual front view SLM 280 chamber and (b) 3D domain used in simulations.

3.1. Mesh independence test

A mesh independence study was performed with three mesh settings of coarse, medium and fine with maximum element sizes of 10, 5 and 2.5 mm respectively using the cut cell method. To satisfy the convergence, the first condition set was that the residuals reduced to 10^{-3} . Secondly, a line surface was applied at the edge of the powder bed to monitor the velocity profile of the inert gas flow. This is to determine that the upstream flow has reached a steady state before the introduction of spatter particles. The energy equation was not accounted for during the mesh independence study to neglect computations on natural convection within the domain. Only after convergence were the spatter particles injected into the domain from the designated position on the powder bed. The simulations were then resumed until all the particles had been accounted for.

3.2. Boundary conditions

The inlet velocity is assumed to have a fully developed velocity profile, while the outlet was given an under-pressure condition due to the presence of suction provided by the gas pump to recirculate the inert gas flow. The no-slip boundary condition was applied on the plate surface.

As seen from Table 1, the temperature of the substrate is prescribed as a heated plate. Due to its relatively high temperature as compared to that of the cross-flow fluid (taken to be 25 °C), natural convection would take place during SLM. A symmetry boundary condition was also set at the side walls of the domain to account for the zero-shear slip. To reduce computation costs, the regions A to D on the powder bed were set to "trap", in order to stop the trajectories of the particles when in contact with these regions. The same condition was also set to the walls.

Particle-particle interactions were neglected and it was assumed that the particles were spherical and non-reacting. In the experiments, the laser scanning region comprised of multiple unidirectional vectors. However, in this study, the dimensions of the ejection sites were 80×0.1 mm (in the x and y axis respectively). The length of 80 mm corresponds to a single scan vector as applied in our earlier work [17], while the width of 0.1 mm or 100 μm represents that of a single melt pool.

3.3. Initial conditions for spatter ejection profiles

Three properties of the ejected spatter particles were considered; (a) particle size distribution, (b) ejection angles and lastly (c) the ejection speeds.

3.3.1. Particle size distribution

It was reported that there are three main types of ejected particles during SLM based on their corresponding ejection mechanisms. The first is due to the recoil pressure exerted on the melt pool surface, causing molten droplets to be ejected at the edges of the melt pool. The other two ejections are due to the entrainment effects and are ejected as hot and cold particles, depending on their initial ejection locations from the local scanning regions. As reported by Ly et al. [4], 15 % of the spatter particle ejections are due to recoil pressure, 25 % from cold and the remaining 60 % are hot ejections. In their work, the hot and cold ejections were stated to have diameters no larger than the fresh powder, at

Table 1: Fluid properties and chamber settings

Property	Symbol	Value	Units
Density	ρ_f	1.63	kg/m ³
Dynamic viscosity	μ	2.23×10^{-5}	kg/(ms)
Mean velocity at bottom gas inlet	u	1.41 & 1.57	m/s
Temperature of substrate	T	150	°C
Chamber pressure	p	0.43	mbar

30 μm , while the size distribution of the particles ejected due to recoil pressure were comparable and some were even larger than the fresh powder.

However, in our earlier experimental study [17], all the analysed particles were bigger in size than the fresh powder as particles smaller than 63 μm had been sieved out. Therefore, we attribute the sizes of the collected particles to be due to possible coalescence effects between molten droplets before solidification, and also sintering between hot ejections as observed by Ly et al. [4]. The application of a greater layer thickness of 100 μm could have also led to the ejection of droplets with larger volume.

To ensure that the simulations follow the experiments as closely as possible, the spatter particle ejection profiles in terms of the size distribution and its corresponding ejection angle and speed were extracted from literature. The particles were spherical with their density set to 2700 kg/m^3 , which assumes that the molten droplets have solidified. The particle size distributions at each gas pump setting were obtained using optical microscopy and is seen in Fig. 3.

To reduce computational costs, the size distribution of the spatter particles injected into the domain were assumed to be similar regardless of the inert gas pump setting. Thus, for each bin or group of sizes in Fig. 3, the average number of particles between the two gas pump settings were obtained. The determined number of particles were then selected randomly correspondingly for each bin.

3.3.2. Ejection angles

Secondly, the ejection of hot spatter particles was set to be in the x-z plane only. The range for the ejection angles was extracted from video data as recorded by Bidare et al. [3] and plotted in Fig. 4. In their work, Schlieren high speed imaging was used to capture the trajectories of hot particles expelled by the laser plume. This includes entrained hot powder and also ejected molten material from the melt pool due to recoil pressure. The laser power and speed was set to

Figure 3: Size distributions of spatter particles collected from experiments where gas pump settings were set at 60 % and 67 %. The average diameters were then derived for each size interval of 17 μm . [17].

200 W and 1 m/s respectively. With a reported layer thickness of 50 μm , the energy density had a value of 33.3 J/mm³.

These values were deemed to be sufficiently similar to that used in our earlier work where the laser power, speed and layer thickness of 350 W, 0.9 m/s and 100 μm respectively, giving an energy density of 32.4 J/mm³. Also with increasing laser power and speed, the ejection of spatter shifted from the forward, to vertically upwards and eventually directed to the rear or the opposite direction as the laser scanning. Therefore, in terms of the ejection angles, the extracted data from the high speed video is deemed to be acceptable representation of the spatter ejection for this study. However, it should be noted that the corresponding sizes of the individual spatter particles were not determined for the data in Fig. 4. Hence, the assumption that the particle size was independent of the ejection angle was made.

By plotting the frequency of the spatter particles against the ejection angle

Figure 4: Initial ejection profiles of 30 hot spatter particles extracted from Bidare et al. [3].

from the data in Fig. 4, the following plot Fig. 5 is obtained. A normal distribution curve is overlaid on the bar chart.

Figure 5: Fitting of a normal distribution plot to the ejection angles of spatter particles which were experimentally observed.

The ejection angles were then obtained randomly based on the normal distribution, and applied to the ejected particles which are elaborated in the next subsection.

3.3.3. Ejection speeds via entrainment effects

Hot and cold particles are ejected due to entrainment effects as reported by Ly et al. [4]. Particles closer than two melt pool widths to the laser irradiation location are quickly swept into the laser beam region and ejected as hot particles. From Fig. 5c of the paper by Bidare et al. [3], it was observed that both hot ejections and molten droplets ejected due to laser induced recoil pressure were entrained by the laser plume. An important point to note is that the two types of high temperature ejections mentioned earlier were difficult to be distinguished from the video data. Also from the collected samples of the earlier experiments, we could not match individual particles to their original ejection mechanisms based on appearance alone. It was also assumed that since the plume was pointed fully backwards, and disrupted the powder layer behind the laser beam, even the recoil pressure driven particles would be subjected to the aerodynamic drag which pulls these droplets towards the plume (entrainment). Thus in this simulation study, both types of ejections have been categorised as entrained particles in order to reduce computational effort.

The ejection velocity due to entrainment effects as reported by Ly et al. [4] is given by

$$v_p = v_g(1 - e^{-\frac{t}{\tau}}); \tau = \frac{2\rho_p R^2}{9\mu} \quad (8)$$

where v_p is the particle velocity, v_g is the gas velocity, τ is the entrainment time, R is the particle radius, ρ_p is the particle density and μ is the gas dynamic viscosity. Following the same principles, for a laser beam diameter of 80 μm and scan speed of 900 mm/s or 0.9 m/s, the particle dwell time $t = 8.9 \times 10^{-5}\text{s}$.

Assuming $t \leq \tau$, $v_p \approx v_g \frac{t}{\tau}$. The plume velocity was also reported to be a few hundred m/s, and from the results on the laser plume velocity distributions by Bidare et al. [3], which is in agreement with that of the gas velocities reported by Ly et al. [4]. The laser plume velocity contour plots as reported by Bidare et al. [3] show that the velocity decreases with height, and the highest velocity is maintained at the core of the plume near the powder bed. Since the locations of the interactions between the entrained particles and the plume varies and indeterminate, the velocity of the plume at a high value of 900 m/s was applied in this study, as it is assumed that the particles would be entrained very closely to the laser beam.

The laser plume was reported to generate a radial flow field in the argon atmosphere, due to momentum conservation, exerting drag forces on surrounding particles [3]. To reduce computation costs, the temperature dependent gas dynamic viscosity of argon is assumed to be constant at a value of 8.9 kg/(m/s) at 2000 K [26].

3.3.4. Summary of ejection profiles

To conclude, the steps taken to determine the input parameters of the each spatter particle were; firstly, the size was sampled from the distribution in Fig. 3. Following that, the ejection angle which was assumed to be independent of the spatter size and ejection types, was determined randomly from the normal distribution in Fig. 5. Finally, the particle speed was computed from Equation 8.

Additionally, the simulations conducted did not fully account for the multi-physics phenomena associated with SLM, such as melting, evaporation, Marangoni effects, recoil pressure and also the induced argon flow close to the laser beam. To replicate such complexities in a single simulation would require critically significant computational power and resources that was not attainable during this

study.

4. Results and discussion

4.1. Mesh independence test

The result of the mesh independence test is shown in Fig. 6 below. It can be seen that the medium mesh made up of a maximum of 5 mm elements generated a maximum velocity of approximately 1 m/s in the -x direction. Taking into account the significantly longer time required to run the simulations using the 2.5 mm mesh elements owing to the use of more computational resources, while giving a result close to that of the medium sized mesh especially for z lower than 0.04 m, the remainder of the simulations were performed using 5 mm elements.

Figure 6: Mesh independence test results for coarse, medium and fine meshed domains.

4.2. Validation with experiment results

The actual imaging of the inert gas flow within the commercial SLM Solutions machines have not been reported in literature. From the CFD simulation

results illustrated in Fig. 7 below, the gas flow near the powder bed is seen to be recirculating along the streamline direction of the domain. Due to the presence of the step near the outlet, the flow is perturbed vertically but still continues its path to the outlet.

Figure 7: Steady state velocity contours on x-z plane showing laminar and uniform argon gas flow near the powder bed for inlet velocity of 1.41 m/s.

Fig. 8 shows the trajectories taken by the spatter particles when the gas flow was initialized at 1.41 m/s. Previously, the spatter particle trajectories have been captured in 3D as reported by Bidare et al. [3]. However, the initial paths taken by the spatter seen in Fig. 4 were only recorded in the x-z plane, with no data recorded for spatter penetration in the y direction. It was observed that spatter ejected with a y direction vector component occurred randomly and thus

were not accounted for in this study. The simulation results from the this work were validated from our earlier experimental data on the spatter distribution on the powder bed as shown in Fig 9 [17].

Figure 8: Profiles of path trajectories for a range of spatter particles for gas flow velocity of 1.41 m/s.

4.2.1. Validation for size distributions

The first validation with the experiment results is on the size distributions of the deposited spatter particles. It can be seen that for regions A to D, the trend in the mean spatter diameter obtained from the simulations is very much similar to that from the experiments. From Fig. 9b, the absolute difference between the simulation and experiment values achieved was as low as 0.6 % as seen in region A while the greatest discrepancy with a value of as high as 61.1 % was

found in region C. From the data reported by Ly et al. [4], there was a decreasing trend for both hot ejections and recoil pressure induced ejections, with increasing diameter of the particles. Thus the larger spatter particles possessed lower initial velocities resulting in significantly shorter distances travelled both horizontally and vertically. Also, as seen from our earlier work [17], the particles that are deposited in regions B to D had Stk numbers close to or greater than 1 due to their large diameter values which reached close to $180\text{ }\mu\text{m}$.

Despite the large contrast in spatter diameters between simulation and experiment results, a good agreement has been reached in terms of the trend of the size distribution. Future simulation studies on the transport of spatter particles by the inert gas flow could incorporate more parameters. These could include collisions between the spatter particles, rotation effects and also the recoil pressure on the ejection of spatter. Accounting for the multi-physics within and above the melt pool such as Marangoni forces, recoil pressure and vaporisation as studied by Khairallah et al. [2], would then provide a more complete and realistic approach to the simulations, from the spatter generation to their transport by the gas flow and finally the deposition or distribution on or out of the powder bed.

In this current study, the ejections due to recoil pressure were neglected, such that it was assumed these particles also ended up being entrained and swept away by the metal vapour and laser plume which had velocities of up to a few hundred m/s [3]. However, recoil pressure driven spatter which accounted for 15 % of the spatter particles in the study by Ly et al. [4] could have resulted in more accurate results being obtained.

Based on the results reported by Ly et al. [4], the melt pool ejections due to recoil pressure and not the entrainment effect have ejection speeds ranging from 3 to 8 m/s. In both the studies performed by Ly et al. [4] and Bidare et al.

(a)

(b)

Figure 9: Bar chart of mean diameter of spatter particles for both experiment and simulations at (a) 60 and (b) 67 % of gas pump setting.

[3], stainless steel powder was used as the input material. The angle of ejection of spatter particles were also projected rearwards, in the opposite direction to that of the laser beam motion. However, our previous work used the aluminium alloy, AlSi10Mg, powder with a thermal conductivity of 146 W/(mK) was used as compared to stainless steel 316L with a value 21.4 W/(mK) [27]. This means that a more intense spatter generation is expected for aluminium alloy.

From the velocity-size distribution plot illustrated in the work by Ly et al. [4], an inverse relationship was established for melt pool ejections which did not involve the entrainment effect. In other words, for spatter particles ejected due to the recoil pressure on the melt pool, the ejection velocity decreases with increasing diameter. This relationship was reported by Kaplan and Powell [28], where it was stated that the threshold for the escape of molten droplets is influenced by the local surface tension, surface geometry, gravity and viscosity. For a spherical droplet with radius of curvature R , the surface tension pressure of a curved surface derived from the Young-Laplace equation is given by

$$\Delta p = \frac{2\sigma}{R} \quad (9)$$

where σ is the surface tension.

The molten droplet ejection condition is possible when the dynamic pressure which refers to the kinetic energy per unit volume of a fluid particle, is sufficient to overcome the surface tension pressure [29] and is given as

$$\frac{1}{2}\rho_L u_L^2 \geq \frac{2\sigma}{R} \quad (10)$$

where ρ_L is the liquid metal mass density and u_L is the vertical component of the velocity. In the study by Ly et al. [4], where $R = 200\mu\text{m}$ and $\sigma = 1.5\text{N/m}$, the escape velocity for stainless steel 316L was found to be approximately 1 m/s

which was in agreement with that reported by Kaplan and Powell [28]. Due to the uneven surface of the melt pool, it was assumed that the molten droplets were ejected normal to the local melt pool surface such that u_L represents the normal velocity component.

However, in this study the escape velocity as a function of melt diameter, which was assumed to be equivalent to the spatter diameter, is established in Fig. 10. The input parameters for the molten droplet escape condition is found in Table 2.

Table 2: Parameters for molten droplet escape condition

Property	Symbol	SS 316L	AlSi10Mg	Units
Density	ρ_L	6881 [30]	2320 [31]	kg/m ³
Surface tension	σ	1.5 [4]	0.705 [32]	N/m

In this work, the temperature at which the molten droplets are ejected from the melt pool (close to the edges) was deemed to be approximately 850 °C or 1123.15 K. This value was determined based on the study by Li and Gu [33] on the temperature distributions of the melt pool during SLM of aluminium alloys. The density was then deduced from the study reported by Assael et al. [31] on the density of liquid aluminium as a function of temperature. The surface tension was then determined from the experimentally obtained relationship between surface tension and temperature established by Dou et al. [32].

From Fig. 10, the escape velocity for AlSi10Mg spatter particles are greater than that of the SS316L across all diameter values. Up to 20 μm diameter, the velocity decreases sharply to approximately 10 m/s from an initial value of 35 m/s for AlSi10Mg. The range of ejection velocity for spatter particles with diameters 60 to 300 μm is from 6.4 to 2.8 m/s. This corresponds to the results reported by Ly et al. [4] where the spatter diameter has an inverse relationship to the ejection velocity.

Figure 10: Plot of spatter ejection velocity against diameter.

Therefore, to put things into perspective, the entrainment driven ejection velocity equation (equation 8) resulted in particles with diameters of $130 \mu\text{m}$ and bigger to have velocities of 2.8 m/s and lower. This means that should the recoil pressure driven particles be accounted for in the simulations, their deposition further downstream of the inert gas flow and possibly outside of the powder bed due to their greater initial ejection velocities. This could lead to more accurate comparisons with the experiments.

4.2.2. Validation for mass distributions

The second validation is with regards to the mass distributions which has been reported in terms of mass percentage. As seen in Fig. 11, the discrepancies between experiment and simulation results are lower throughout all regions. At gas pump settings of 60 and 67 %, the differences range from 2.8 to 27.8 % and 0.7 to 29.7 % respectively. Therefore, an even better agreement between experiment and simulation results has been established as compared to the size

distributions.

(a)

(b)

Figure 11: Bar chart of mean mass percentage of spatter particles for both experiment and simulations at (a) 60 and (b) 67 % of gas pump setting.

4.3. Effectiveness of inert gas cross-flow

To observe the effectiveness of the inert gas cross-flow, a control simulation was performed where the velocity at the inlet was initialized at 0 m/s. This highlights another advantage of performing spatter transport simulations since in the commercial SLM machines, inert gas has to be pumped into the chamber to remove the harmful by-products such as condensed and oxidised metal vapour and plasma plumes which often get deposited on the laser lens even with the presence of inert gas flow. The presence of such contaminants on the laser lens would perturb the focal point of the laser beam leading to inaccurate energy input at the powder bed during laser scanning.

The trajectories of the spatter particles in the absence of the inert gas cross-flow are illustrated in Fig. 12. It is clear when comparing Fig. 8 and Fig. 12 that the trajectories are extended due to the presence of the inert gas flow, especially for the smaller particles, which are illustrated by the blue lines. To quantify the effect of the inert gas flow, the size and mass distributions for the case of no gas flow is compared with those including gas flow in Fig. 13 and 14. It can be observed that all of the spatter particles were deposited on the powder bed with their less steeper gradient for the size distribution. For the mass distribution however, more than 40 % of the spatter particles accumulated in region D. Therefore, the presence of the inert gas flow has shown to generate a more even distribution of spatter particles downstream of the spatter injection locations or for the case of SLM, the laser scanning sites.

As reported by Ladewig et al. [13], the SLM process by-products were observed to deposit near the outlet, due to the regions of low inert gas flow velocities at those areas. From Fig. 8, it can be seen that this is indeed the case since the velocity of the gas decreases with distance over the powder bed. Thus, it was suggested that further optimisation on the designs of the gas flow inlet

Figure 12: Profile of path trajectories for a range of spatter particles without gas flow.

Figure 13: Bar chart of mean diameter of spatter particles in regions A to D at no gas flow, and gas pump settings of 60 % and 67 %.

Figure 14: Bar chart of mass percentage of spatter particles in regions A to D at no gas flow, and gas pump settings of 60 % and 67 % .

and outlets should be studied in order to maintain the gas flow velocities over a longer distance. The resulting favourable pressure gradient which enables the laminarization of the flow which would then allow for a more effective removal of the spatter particles [34] .

A parametric study on the inlet and outlet designs was conducted by Philo et al. [23], showed that the flow uniformity was indeed influenced by the gas flow inlet and outlet designs. It was also noted in their work that "the removal of spatter particulates remain unclear". Therefore, our work has proven for the first time, that even with the presence of the inert gas flow, the spatter particles were not effectively removed over the powder.

Lastly, another aspect to consider during the simulations is the distribution of spatter in the y directions. These could have originated either from the initial spatter ejections or due to the gas flow structures within the chamber. In this study, such details were not incorporated into the current work although it has been reported by Bidare et al. [3]. An additional high speed camera

simultaneously capturing the top or side view (x-y or y-z plane) would then provide a three-dimensional stereoscopic evidence into such insights [35].

5. Conclusion

During SLM, powder bed contamination often takes place due to the undesired deposition of by-products such as spatter particles which get ejected from the melt pool. The removal of such contaminants in commercial SLM systems is done by the inert gas cross-flow directly above the powder bed. In this work, the effectiveness of the spatter transport by argon gas flow, accounting for the initial particle ejection profiles have been performed using CFD-DPM, to investigate the distribution of spatter on the powder bed. Good agreement in terms of the size and mass, between the simulation results and previous experimental data has been established further downstream of the gas flow. It was shown that the gas flow was not effective in removing the larger spatter particles in the -x direction. Despite not including the complete multi-physics of the SLM and spatter ejection phenomena, the current simulations was able to illustrate the effects of the gas flow on the trajectories of the spatter particles and predicted their eventual deposition on the powder bed. Therefore, they can be applied in future iterative designs of gas inlets to optimise spatter removal in commercial SLM systems by considering the initial ejection profiles of the spatter particles based on the entrainment effects by the metal vapour and laser plume.

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