

**SIMULATION OF INERT GAS FLOW AND SPATTER
TRAJECTORIES IN LASER POWDER-BED FUSION**

BY

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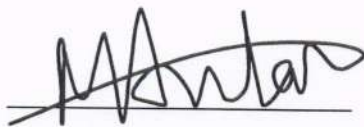
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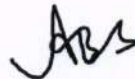


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DEDICATION

This thesis is dedicated to my parents, whose sacrifices and dedication have shaped the foundation of my character and instilled in me the values of perseverance and hard work. To my beloved wife, Khizran, whose patience, understanding, and unwavering support have been my source of strength, motivating me to overcome challenges. And lastly, to my precious sons, Jamal and Khalid, whose laughter have brought immeasurable joy into my life. Thank you.

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LIST OF ABBREVIATIONS

AM	:	Additive Manufacturing
CAD	:	Computer Aided Design
CFD	:	Computational Fluid Dynamics
DPM	:	Discrete Phase Model
HWA	:	Hot Wire Anemometer
LPBF	:	Laser Powder-bed Fusion
PIV	:	Particle Image Velocimetry

ABSTRACT

Full Name : [Aremu Oluwatobi Habib]
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Laser powder-bed fusion (LPBF) process is widely employed in various industrial applications due to its capability to produce complex geometries. Despite its advantages, various challenges affecting the repeatability of the process have hindered its widespread adoption. One of these challenges, notably, spatter ejection, impacts the surface roughness, introduces porosity, and creates defects in printed parts. While inert gas flow in the build chamber is recognized as a key parameter in removing spatters from the build plate, its non-uniform distribution in the build chamber limits its effectiveness. This study employs validated Computational Fluid Dynamics (CFD) simulations to examine spatter trajectories and assess the impact of inert gas flow rates on spatters of different sizes and materials ejected at different angles and locations on the build plate. It was observed that spatters landed on the build plate either by direct deposition, conveyance by airflow, or redirection within the recirculation zone. For the baseline design with a 250 LPM gas flow rate, all 60 μm spatter particles of AlSi10Mg, SS316L, and Hastelloy X ejected at 20° in the flow direction were successfully transported outside the build plate. Most 120 μm spatters ejected from the middle of the build plate were deposited outside the build plate, while all 180 μm spatters landed on the build plate, irrespective of ejection location and gas flow direction.

ملخص الرسالة

الاسم الكامل: ألوتتي حبيب اريمو

عنوان الرسالة: محاكاة تدفق الغاز الخامل ومسارات الترشيح في اندماج طبقة المسحوق بالليزر

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تُستخدم عملية دمج طبقة المسحوق بالليزر على نطاق واسع في العديد من التطبيقات الصناعية نظرًا لقدرتها على إنتاج أشكال هندسية معقدة. وعلى الرغم من مزاياها، فإن التحديات المختلفة التي تؤثر على تكرار العملية أعاقت اعتمادها على نطاق واسع. أحد هذه التحديات، وأبرزها طرد الرذاذ، يؤثر على خشونة السطح، ويسبب المسامية، ويخلق عيوبًا في الأجزاء المطبوعة. في حين يتم التعرف على تدفق الغاز الخامل في غرفة التصميم كمعلمة رئيسية في إزالة البقع من لوحة التصميم، فإن توزيعه غير الموحد في غرفة التصميم يحد من فعاليته. تستخدم هذه الدراسة عمليات محاكاة ديناميكيات الموائع الحسابية المعتمدة لفحص مسارات التناثر وتقييم تأثير معدلات تدفق الغاز الخامل على الرذاذات ذات الأحجام المختلفة والمواد المقذوفة بزوايا ومواقع مختلفة على لوحة التصميم. وقد لوحظ أن الرشاشات هبطت على لوحة البناء إما عن طريق الترسيب المباشر، أو النقل عن طريق تدفق الهواء، أو إعادة التوجيه داخل منطقة إعادة تم بنجاح نقل جميع جزيئات الترشيح مقاس LPM التدوير. بالنسبة للتصميم الأساسي بمعدل تدفق غاز يبلغ 250 المقذوفة عند 20 درجة في اتجاه التدفق خارج لوحة Hastelloy X و SS316L و AlSi10Mg ميكرومتر من 60 التصميم. تم ترسيب معظم الرشاشات التي يبلغ طولها 120 ميكرومترًا والتي تم إخراجها من منتصف لوحة التصميم خارج لوحة التصميم، في حين هبطت جميع الرشاشات التي يبلغ طولها 180 ميكرومترًا على لوحة التصميم، بغض النظر عن موقع القذف واتجاه تدفق الغاز.

CHAPTER 1

INTRODUCTION

1.1 Background

Additive manufacturing (AM) has surfaced as a revolutionary technology in the manufacturing domain. In contrast to the conventional subtractive processes, AM creates objects through a layer-by-layer methodology. This technique facilitates the production of intricate geometries that pose challenges for traditional manufacturing methods. Moreover, AM minimizes material wastage, amplifies design flexibility, and expedites the manufacturing of prototypes and commercial parts [1]–[3].

AM technologies, particularly metal additive manufacturing processes, have seen widespread usage in a variety of industrial applications in recent years. Metal AM processes offer advantages such as design flexibility, providing the freedom to create intricate and customized designs. Additionally, these processes enable localized manufacturing, allowing for the production of components in specific geographical locations or on-demand [2], [3]. Numerous techniques exist for metal AM; nevertheless, laser powder-bed fusion (LPBF) has risen to prominence as one of the most favored and extensively utilized methods across various industrial applications. This preference is attributed to its notable attributes of high accuracy and reliability [4].

In a typical LPBF process, metal powder is locally melted by a laser in a layer-by-layer manner, and successive layers are fused together, imparting strength and cohesiveness to the final component [3]. However, the presence of laser beam induces the formation of metal vapor, fostering the ejection of spatters from the powder-bed [5]. These spatters have the potential to land back on the build plate, consequently leading to defects in printed parts [5], [6]. The defects arising from spatters contribute to lower mechanical properties and a decline in the reproducibility and reliability of AM products [6]. The challenges associated with spatter removal contribute to the lack of reliability and repeatability in AM parts, impeding the widespread adoption of LPBF systems [7], [8].

LPBF machines use inert gas flow (Argon or Nitrogen) inside the build chamber to transport the ejected spatter particles away from the build plate. However, not every ejected particle is carried away from the build plate, as some areas within the build chamber experience reduced gas flow velocity, rendering these zones prone to spatter deposition [5]. Nevertheless, the inert gas flow reduces the effect of spatter particles on the quality of manufactured AM parts. Therefore, inert gas velocity is a significant process variable that can improve the process repeatability of AM components and has been investigated in many studies [2], [9].

Numerical approaches for modeling inert gas flow in LPBF encompass CFD methodologies, employing diverse strategies to capture the flow field and turbulence within the build chamber [10]–[13]. Several authors have utilized the DPM to capture the ejected spatter trajectories, and identify spatter rich regions on the build plate [10], [14]. According to their findings, smaller spatter particles were carried further from the build plate whereas bigger spatter particles were not removed effectively by gas flow.

Likewise, findings from the literature reveal various experimental approaches employed to analyze inert gas flow in LPBF systems [15], [16]. These approaches can be categorized into the examination of gas flow velocity profiles and the analysis of particle trajectories. The former is mostly done using hot wire anemometer [16], while the latter is mostly achieved using various optical systems [17]. As most of the works discuss the inlet parameters such as inlet height, inlet width, and outlet height [16], [18], they do not discuss the influence of spatter size and material.

This study aims to evaluate the spatter trajectories, determine the optimal gas flow rate, and identify spatter rich areas based on the ejection location, direction, angle, size, flow rates and material in a Renishaw AM250 chamber using Ansys Fluent Computational Fluid Dynamics (CFD) package. The validated model was used to study the effect of inert gas flow rates on spatters of different sizes (60, 120, and 180 μm) and materials (AlSi10Mg, Stainless steel 316L and Hastelloy X), from different ejection locations and ejection angles (20°, 45°, and 70°) in the flow direction and opposite the flow direction. It should be noted that the results presented in this work are taken from [19], [20]. The insights gained from this work will help in identifying areas on the build plate that are more susceptible to spatter deposition, enable design modifications in the LPBF inlet and outlet design along with a reduction in spatter deposition on the build plate, ultimately resulting in higher part quality and reliability.

1.2 Motivation

The presence of spatters during the LPBF process has been reported in several studies to reduce the quality of the parts built, thereby, reducing the reproducibility and reliability of additively manufactured products [6]. The lack of reproducibility and reliability of AM

parts can be partially attributed to the inadequate removal of spatter, thereby impeding the widespread adoption of LPBF systems.

To improve the repeatability and the reproducibility of parts built with LPBF systems, it is essential to determine the optimal flow rate for different materials, and to study their spatter trajectories. Numerous simulation studies documented in the literature have investigated the spatter removal process, emphasizing the gas flow rate as a crucial parameter [2], [18]. Nevertheless, a sole focus on gas flow rate proves insufficient due to the non-uniform nature of inert gas flow within the build chamber, leading to inadequate transport of all spatters away from the build plate. Consequently, a comprehensive investigation into both the gas flow rate and the trajectories of spatters ejected in the LPBF process becomes imperative. The precise identification of such areas holds the potential to mitigate spatter contamination in printed components, thereby enhancing the overall quality of LPBF-produced parts.

1.3 Objectives

This thesis focuses on simulation of inert gas (shielding gas) flow as well as the spatter trajectory in the build chamber of the laser powder-bed fusion machine to observe:

- I. Spatters trajectories of different materials ejected from different locations, at various ejection angles using the baseline design with 250LPM gas flow rate in Renishaw AM250 build chamber.
- II. Effect of the gas flow in the recirculation zone on spatter trajectories using the baseline design with 250LPM gas flow rate in Renishaw AM250 build chamber.
- III. Effect of gas flow rates on the transport of spatters in the build chamber using 4 different flow rates.
- IV. Identify the best flow rate for effective spatter removal for different spatter sizes.
- V. Identify the optimal flow rate for aluminum alloy AlSi10Mg and stainless steel SS316L for effective spatter removal.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Additive Manufacturing

Additive manufacturing (AM) technologies are emerging techniques capable of manufacturing complex parts that cannot be produced conveniently through conventional or subtractive manufacturing [21]. Contrary to conventional manufacturing, AM parts are built layer-by-layer in a bottom-up approach until the final shape is attained. Despite the fact that additive manufacturing has been in existence for more than two decades, it has only recently begun to emerge as an industrial manufacturing process [22].

Additive manufacturing is synonymous to 3D printing, rapid prototyping, layer manufacturing, automated fabrication and solid freeform fabrication [1]. AM processes have several advantages as they can be used to produce parts with complex geometry with low cost, quick prototyping, mass customization and reduction of material waste [23], [24].

AM processes can be classified based on different measures such as raw material, baseline technology, etc [1]. There are seven (7) major AM technologies with many sub-divisions under each technology. The major technologies are Vat-photopolymerization [25], [26], Material extrusion [26], [27], Sheet Lamination[26], [28], Direct Energy Deposition [26], [29], Material Jetting [26], Binder Jetting [26], [30] and Powder-Bed Fusion [31], [32].

Metal AM techniques are widely used for various industrial applications, such as, aviation, dental and automotive industries [33], [34]. Amongst the numerous metal AM techniques,

laser powder-bed fusion (LPBF) is extensively employed in diverse industrial applications owing to its reliability and high accuracy [4].

2.2 Laser powder-bed fusion

Laser powder-bed fusion (LPBF) is one of the most commonly utilized metal AM technology because it can manufacture near full dense metal components from a variety of engineering alloys [35]. Like other AM technologies, the LPBF process involves many stages, which commences with the 3D CAD design. The CAD file is then converted into a STL file that can be read by the machine. As illustrated in Figure 2.1a, the building procedure starts with the re-coater or wiper blade spreading a thin layer of metal powder onto a build plate in the build chamber. The powder is selectively melted and fused using a laser. Then, the build platform is lowered, and a new layer of powder is added to the powder-bed before the next laser scanning. The process is then repeated until the part is fully constructed. A nitrogen or argon gas inert atmosphere is often introduced in the build chamber during LPBF to prevent oxidation and transport spatter away from the build surface [36]. The schematic diagram of the LPBF setup is shown in Figure 2.1a. Scanning speed, hatch spacing, laser power, and layer thickness are some of the most important build parameters (Figure 2.1b) in the LPBF process [37].

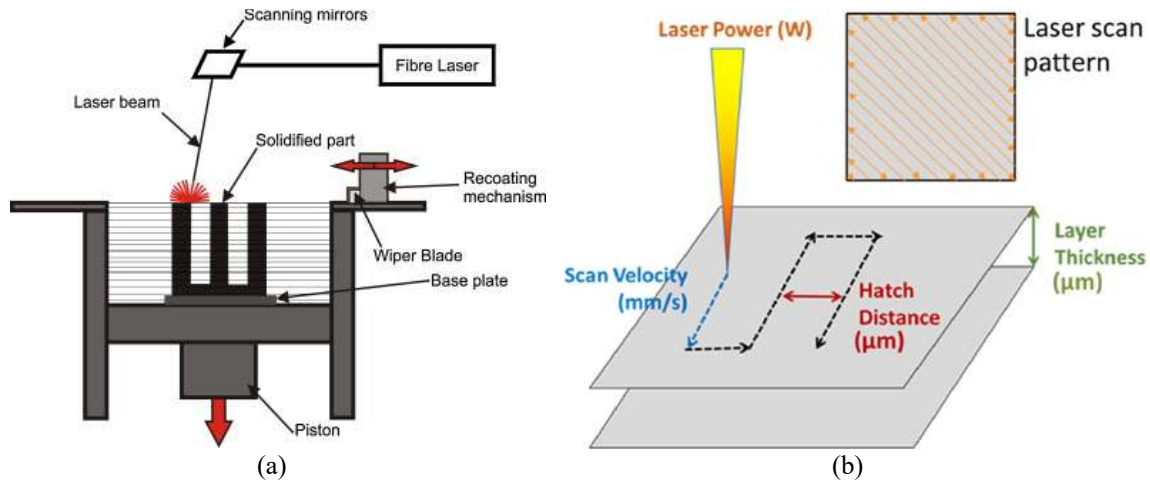


Figure 2.1: (a) Schematics of the laser powder-bed fusion (LPBF) process and (b) LPBF process parameters [32], [38]

The interaction between the laser and the powder-bed usually leads to the ejection of spatter particles that affect the LPBF part quality [12], [39]. In the absence of a removal process, spatters may re-deposit on the build area via gravity and contaminate the build area, thereby affecting the part's quality [40]. To mitigate the contamination of components by ejected particles, the prevalent method for spatter removal involves the utilization of inert gas flow within the build chamber [6], [41].

Researchers have concluded that removal of spatter particles from the build chamber affects the properties of the printed samples. Anwar and Pham [42] evaluated the tensile strength of LPBF AlSi10Mg parts and found that more spatters were transported away when the inert gas flow was increased, thereby improving the part quality. Similarly, Kong et al. [43] implemented a modified inert gas inlet baffle to enhance gas flow uniformity, resulting in improved properties of LPBF Ti6Al4V parts. Despite the significance of inert gas flow in LPBF, only a few studies have examined the interactions between cross-flow dynamics and spatters [15]. However, to properly understand the inert gas flow and spatter removal, it is important to study the experimental and simulated works. Further details will be discussed in the next section.

2.3 Experimental Approach to Gas Flow and Spatter Measurement

2.3.1 Materials

The inert gas employed in the LPBF process serves a dual purpose. Firstly, it establishes an inert atmosphere within the build chamber to prevent oxidation of the printed parts. Secondly, it functions as a means to convey spatters away from the build plate, in order to produce high quality parts [42]. Argon gas is predominantly used as the inert gas in the majority of experimental studies, given its prevalence as the most common inert gas in commercial LPBF machines.

Figure 2.2 shows various types of powder materials utilized in the experimental studies. It can be observed from Figure 2.2 that AlSi10Mg is widely used in the experimental studies of inert gas flow as it is commonly used in automotive and aerospace industries [44]. Due to their widespread use in industrial applications, researchers have also investigated other Al powders [45]–[47].

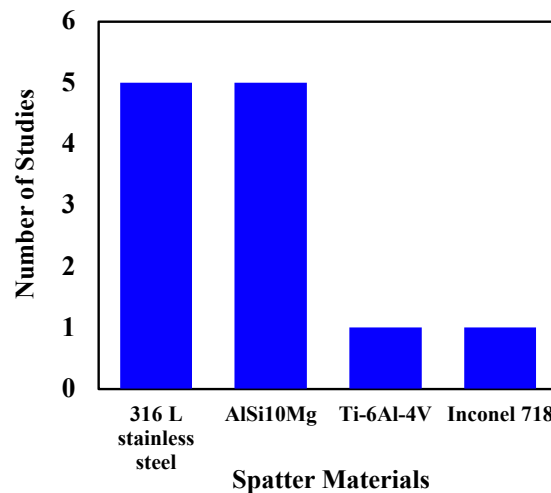


Figure 2.2: Summary of the common materials used as powder materials in the experimental studies involving spatter tracking reviewed in this study

2.3.2 Experimental Equipment

Various types of LPBF machines were documented in the studies, as illustrated in Figure 2.3. These include AM-250 LPBF system from TongTai Machine & Tool Ltd., Taiwan [15], a twin laser SLM Solutions 280 HL machine [17], [42], Renishaw AM250 [16] (Figure 2.3a), EOS M280 [3], ReaLizer SLM50 [48], EOS M290 [49] (Figure 2.3b), and MTT ReaLizer SLM250 [2].



Figure 2.3: Laser powder-bed fusion machines used for experimental studies (a) Renishaw AM250 [50] (b) EOS M290 [49] (c) SLM Solutions 280HL [51] (d) TongTai AMP 250 [52]

2.3.3 Flow Field Measurement

To accurately simulate the inert/shielding gas flow field within the LPBF build chamber, it is crucial to acquire the initial conditions of the flow field through experimental approaches. Sun et al. [53] categorized the common airflow measurement into 2 distinct groups; the point-wise technique and the global-wise technique. The point-wise techniques include methods such as vane anemometry, laser dropper anemometry, ultrasonic anemometry, and hotwire anemometry while the global-wise methods encompass particle tracking velocimetry, particle streak velocimetry, and particle image velocimetry. Global-wise approaches are capable of capturing airflow velocity fields across the entire domain without displacing the measurement sensors, ensuring minimal interference with the airflow [54]. Of all the methods mentioned, PIV, vane anemometer, and HWA are the prevalent methods employed to investigate the flow properties in the LPBF build chamber [55]. The PIV system, equipped with a high-speed camera, laser, tracer particles, optical lens, particle implantation device, and PIV analysis software, facilitates the determination of inert gas flow velocity distribution in the LPBF build chamber. PIV functions by introducing tracer particles into the flow field, allowing the measurement of flow velocities through the displacement of these particles in captured images [56]. Vane anemometry can also be used for air flow measurements but is not frequently used due to its broad cross-sectional sampling [57].

On the other hand, HWA is the most commonly used tool for flow field velocity measurements in the build chamber [15]–[17]. HWA measures the gas velocity more precisely than vane anemometers as it does not sample a wide cross-section and does not require the insertion of smoke, oil droplets, or particles (for quantitative particle image

velocimetry) [55]. HWA has been employed in several studies and uses the cooling effect of a heated thin wire or film that is caused by the motion of its surrounding fluid [58]. Chien et al. [15] used HWA for fluid flow measurement in the LPBF build chamber. Similarly, Philo et al. [16] used the HWA for flow measurement in a Renishaw AM 250 build chamber where a perspex screen with a series of holes was installed to insert the HWA probe (Figure 2.4a). The results obtained were later used to validate the gas flow velocity results obtained from the CFD simulation.

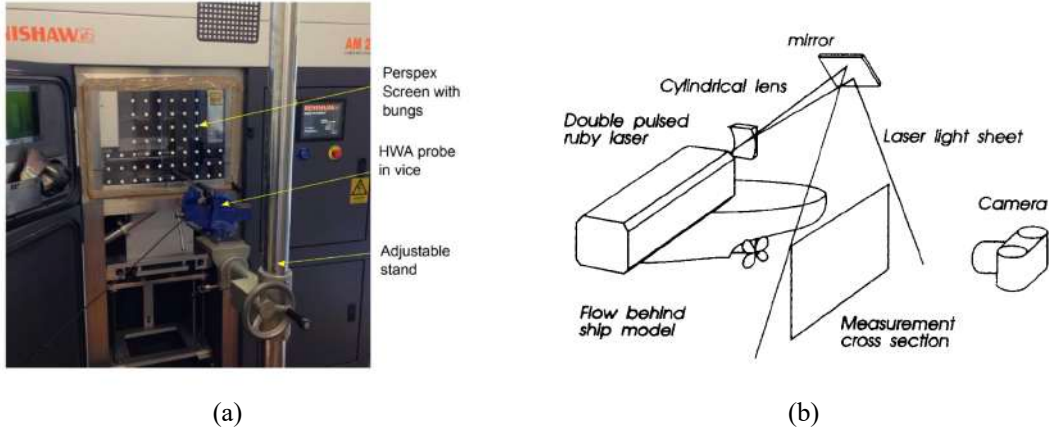


Figure 2.4: Schematic of the common gas flow measurement setups used in laser powder-bed fusion (LPBF) chamber (a) Hot wire anemometer (HWA) [16] (b) Particle image velocimetry (PIV) [59]

2.3.4 Spatter Measurement

Other than the gas velocity profile, determining the initial conditions of spatter particles is crucial for accurately simulating the spatter transport process within the LPBF build chamber [10], [15], [16]. Initial conditions of the spatter such as, initial velocities, initial shooting angles and spatter diameters are determined experimentally [16]. The spatters are usually observed using camera systems. For example, Anwar and Pham [17], used a Sony alpha A6000 camera to capture images of spatters during the LPBF process. Similarly, Chien et al. [15] used a high-speed CMOS camera while Liu et al. [39] used AOS SPRI-

F2 high-speed camera for spatter tracking. Likewise, Barrett et al. [49] used a pair of synced FPS1000 high speed cameras. In cases where the camera system is non-coaxially configured, the captured video series can be systematically processed frame-by-frame through the application of perspective transformation code in MATLAB [15] or other softwares such as; ImageJ and Open Source Computer Vision (OpenCV) [17], [42]. Figure 2.5 shows the camera layouts used in literatures to observe spatter and inert gas flow in LPBF systems.

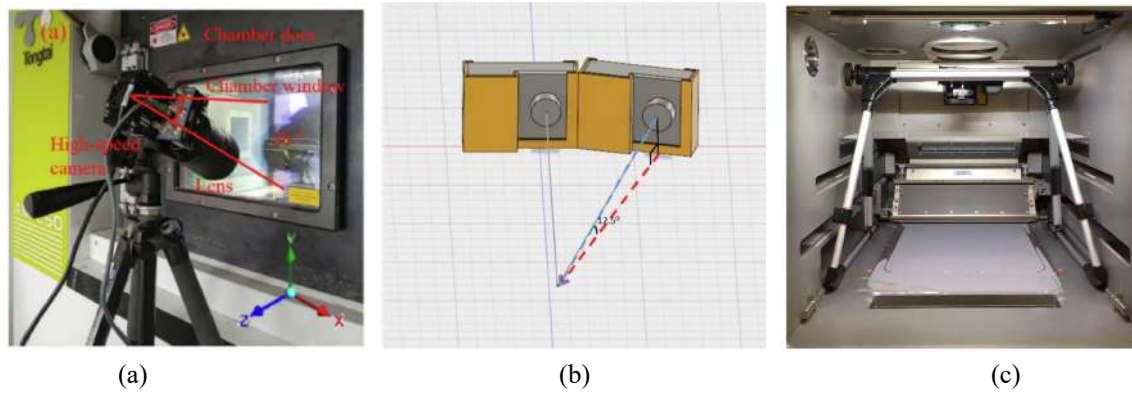


Figure 2.5: Camera setups used in literature to observe and track spatters trajectories In the LPBF chamber
(a) Single non-coaxial camera [15] (b) Double cameras [49] (c) Single camera mounted over the powder-bed [17]

2.4 Simulation Approach to Gas Flow and Spatter Observation

2.4.1 Software

In order to simulate the flow field and gas particle interaction, a finite element analysis software which is capable of doing CFD is required. Since the simulation is regarded as a fluid flow (the flow of the shielding gas), with particle ejections, a CFD finite element analysis software capable of simulating multiphase flow (shielding gas and spatters) is required. In most of the studies (Figure 2.6), Ansys Fluent was the software preferred to

carry out the simulation. Other software used in other studies are COMSOL Multiphysics and CFD ACE+ [42], [56], [60].

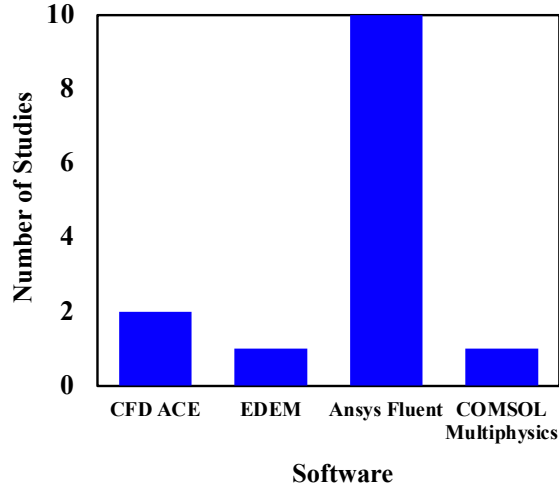


Figure 2.6: Commercial software used for simulation of gas flow and spatter trajectories in the LPBF build chamber

2.4.2 Gas Flow and Spatter Interaction Analysis Workflow

Figure 2.7 illustrates a typical finite element method workflow to simulate the gas flow velocity, uniformity, and spatter interactions in LPBF systems. The CAD geometry of the LPBF machine, the mesh, the initial and boundary conditions, and the fluid (shielding gas) and particles (spatters) properties are the pre-defined inputs to the FEA simulation. In order to consider the forces that occur between particles and fluid, coupling is typically used. One-way coupling reduces the computation time and is the most commonly used approach to capture the influence of gas flow on solid particles accurately since the fluid flow and particle interaction is assumed to be dilute [8], [16] and therefore does not require quantification of particle-particle interactions.

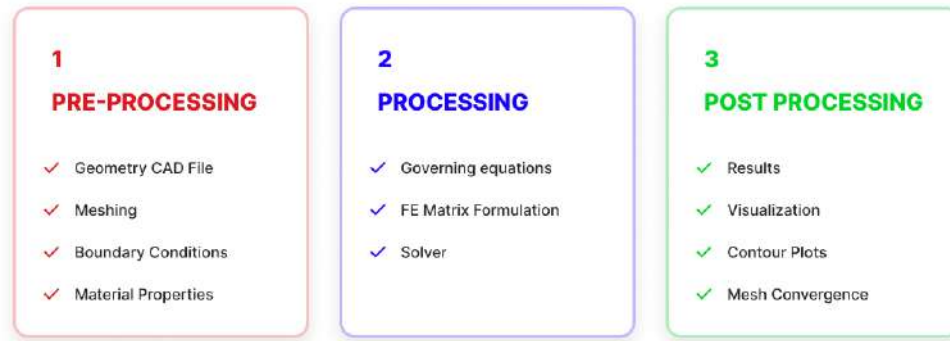


Figure 2.7: Overview of the steps involved in solving a finite element analysis problem

2.4.3 Geometry

In order to accurately represent the build chamber, it is essential to develop a 3D CAD geometry using appropriate CAD design tools. The Renishaw AM250 build chamber used in this work has been used by several researchers as shown in Figure 2.8a-d. For instance, Figure 2.8d shows the ejection locations in Renishaw AM250 build chamber studied by Alquaity and Yilbas [8] while Figure 2.8c shows the Renishaw geometry used by Zhang et al. [12]. Additionally, studies that conducted both experimental and numerical analysis customized their build chamber geometries based on the specific machines they utilized [56], [60].

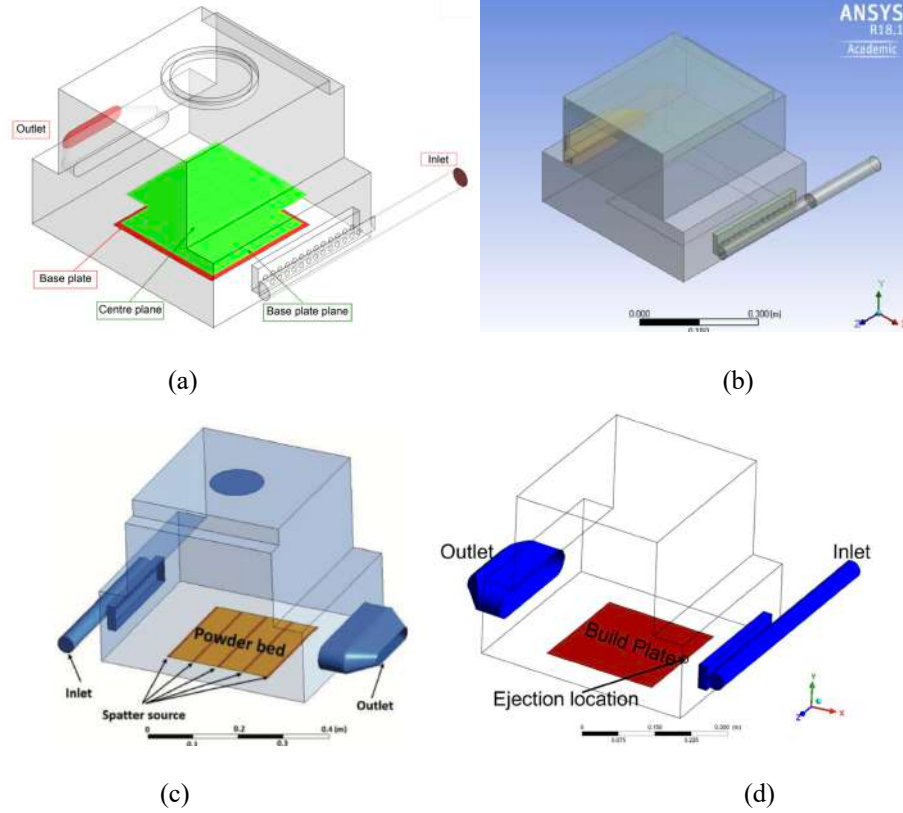


Figure 2.8: Sketches of Renishaw AM250 build chambers used for simulations from different authors (a) Philo et al. [16] (b) Chen et al. [18] (c) Zhang et al. [12] (d) Alqaity and Yilbas [8]

2.4.4 Meshing

The accuracy of finite element analysis results hinges on the characteristics and quality of the underlying mesh. An inadequate mesh has the potential to yield inaccuracies in numerical computations. Additionally, the time required for the analysis is notably affected by mesh quality. Gas flow simulations commonly employ varying mesh densities across different sections of the CAD model. Areas in close proximity to the inlet and wall boundary necessitate a dense mesh for precise analysis, as noted in [18], [61]. Conversely, less critical regions can utilize a coarser mesh to conserve computational resources. Inflation layers are strategically placed near the inlet and walls to effectively capture flow

field velocity and other parameters, especially in regions with sharp gradients (at boundary) [13], [18].

Furthermore, mesh independence or grid independence studies are performed with different mesh settings (Figure 2.9) to ensure convergence and mesh independence [10]. To satisfy convergence, some studies set the residuals to 10^{-3} . However, most studies reduced the residuals criteria to 1×10^{-4} [12], [16].

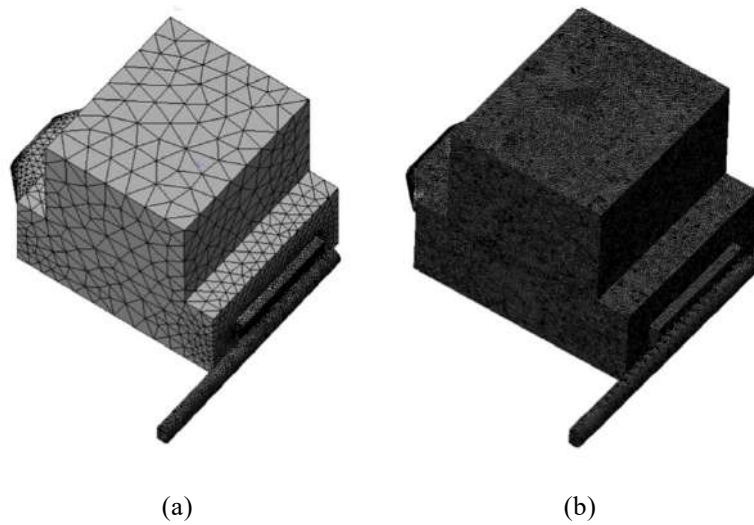


Figure 2.9: Mesh used for simulation (a) Coarse (b) Fine mesh

2.4.5 Computational Model

a) Computational Fluid Dynamics (CFD)

The flow field inside the LPBF build chamber is often evaluated using CFD simulations. The transport of the spatter particles by the shielding gas flow involves the interaction between shielding gas (gas) and the spatter particles (solid). Given that the lift and drag forces acting on the spatter particles determines their motion in general, and the particle-to-particle collision have no significant impact on the particle motion, the flow in the build chamber can be considered a dilute flow [10], [15], [61].

The CFD with the Eulerian-Lagrangian model, is commonly used for gas flow simulations that involve the conservation of mass and momentum. However, when simulating the trajectory of spatter particles, the discrete phase model is usually employed in addition to the CFD [15], [16].

The mass and momentum conservation from the continuity and Navier-Stoke's equation is stated below [8];

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{Equation 2.1}$$

$$\rho u_i \frac{\partial u_j}{\partial x_i} = - \frac{\partial p}{\partial x_j} + \mu \frac{\partial^2 u_j}{\partial x_i \partial x_i} \quad \text{Equation 2.2}$$

where ρ represent the density of the inert gas, u_j represents the velocity vector, p represents the static pressure, μ is the dynamic viscosity, f_j is the gravitational force per unit mass, x_i is the spatial vector, and t is the time.

b) Discrete Phase Model

The Discrete Phase Model (DPM) in Ansys Fluent was used in most studies to simulate the spatter trajectories in the flow field in a Lagrangian manner [8], [13]. In order to consider the forces that occur between particles and fluid, coupling is typically used. The most popular method for correctly capturing the effect of gas flow on solid particles is one-way coupling since it assumes that the fluid flow and particle contact are diluted [10], [11]. Under DPM, each spatter particle's trajectory is determined by solving its force balance equation. This equation relies primarily on the drag force exerted on the particle by the inert gas and the force of gravity (Equation 2.3). The force balance equation and the drag force per unit mass (F_D) are presented below [8]:

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} \quad \text{Equation 2.3}$$

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D Re_{rel}}{24} \quad \text{Equation 2.4}$$

where $\vec{u}$ is the velocity of inert gas, $\vec{u}_p$ is the velocity of spatter particle, $\vec{g}$ is the acceleration due to gravity, ρ_p is the particle density, μ is dynamic viscosity of the inert gas, d_p is the particle diameter, C_D is the drag coefficient for smooth particles, and Re_{rel} is the relative Reynolds number. More details on the appropriate drag coefficient for smooth particles are presented in [62]

Moreover, in a study conducted by Chien et al. [15], the Discrete Element Method (DEM) using EDEM software was favored over DPM for simulating spatter trajectories. This preference was due to the coupled CFD-DEM framework's ability to seamlessly establish a powder-bed with fluid flow (inert gas) and spatter particles. This approach was adopted to account for the implementation of the packed powder and its dynamic behavior.

c) Turbulent Flow Model

In the majority of studies, the flow was assumed to be steady, incompressible and turbulent [10]–[12]. The $\kappa - \epsilon$ turbulence model has been found to be the most suitable turbulence model for simulating gas flow in the build chamber and is given as [10], [63]:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \epsilon \quad \text{Equation 2.5}$$

$$\frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} \quad \text{Equation 2.6}$$

where u_i is the velocity component of the fluid, μ_t is the eddy viscosity, G_k is the turbulence kinetic energy generation by mean velocity gradients, G_b represents the turbulence kinetic energy generation by buoyancy. σ_k and σ_ϵ is the turbulent Prandtl numbers for k and ϵ respectively. $C_{1\epsilon}$, C_2 , and $C_{3\epsilon}$ are constants.

d) Boundary Conditions

To describe the dynamics of the flow inside the build chamber, the fluid flow is typically assumed to be an incompressible ideal gas and a Newtonian fluid [8], [64]. Typically, two types of “Wall” boundary conditions with DPM settings are allocated to all the inner chamber walls within the build chamber [11]. The DPM trap wall boundary condition is configured to halt particle motion upon contact with the walls [8], [11]–[13]. Furthermore, with a reflect wall boundary condition set on other inner walls, the spatters rebound off of the wall with a modified momentum [11], [12]. In the majority of studies, the build plate (powder-bed) was assigned a "trap" boundary condition to halt particle motion upon contact. For instance, Zhang et al. [11] used a trap boundary condition for the build plate, while the other walls were set to "reflect". In contrast, Anwar et al. [10] used a trap boundary condition for all walls, including the build plate in order to reduce the computational costs.

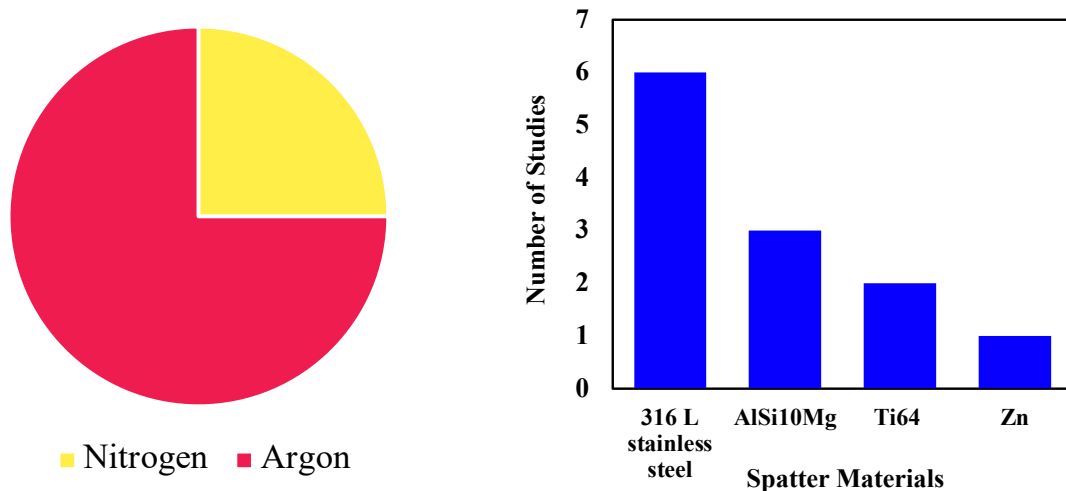
Simulating fluid flow behavior inside the build chamber requires precise inlet and outlet boundary conditions. This involves setting parameters such as the velocity magnitude, turbulence properties, pressure, operating temperature, etc. The inlet condition of the inert gas used in most studies was defined in terms of velocity [10], [63], or flow rates [8], [18],

[61]. On the other hand, the outflow boundary condition is usually employed to define the outlet boundary condition [8], [11].

2.4.6 Materials Simulated

The interaction between the laser and the powder-bed typically results in the ejection of spatter particles, representing one of the in-process factors that can adversely affect the quality of laser powder-bed parts [5], [12], [39]. Due to gravity, the spatters may re-deposit on the powder-bed in the absence of any removal procedure, thereby reducing the quality of the component being manufactured [40].

The shielding gas transports spatters away from the build plate in order to avoid deposition of spatters on the build plate [5]. In the majority of studies, Argon gas was utilized as the shielding gas [11], [17], confirming its prevalence as the most common inert gas in commercial laser powder-bed fusion machines. However, in some works, [15], [64], Nitrogen was used as the shielding gas [66] - [69]. Figure 2.10a shows the breakdown of different kinds of inert gas used in the studies while Figure 2.10b discusses the various materials used in numerical studies for inert gas flow.



(a) (b)
Figure 2.10: (a) Gases used as inert gas in the build chamber for simulating the gas flow (b) Spatter materials simulated in the studies reviewed

2.4.7 Particle Size

In most studies, spatter particles were observed with irregular shapes and properties [10], [15]. The variations in the spatter size were due to the machine, material and choice of experimental data used for validations. Spatter powders in all studies were found to have a higher average size compared to fresh powders with satellites on their surfaces. Some spatter powders were also found with clustering and presence of oxide layers [6], [42]. Some of these observations for spatters and virgin powders are shown in Figure 2.11. Figure 2.11a-b show the virgin spherical and spatter particles of AlSi10Mg powders respectively. Spatters show a much bigger size and relatively irregular shapes due to clustering [42]. Similar results are also observed with Hastelloy X as Esmaeilizadeh et al. [6] reported an average size of 40 μ m for fresh powder (Figure 2.11a), 100 μ m for the spatters (Figure 2.11d) [6]. Similarly, Ali et al. [5] classified 17 – 4 PH stainless steel spatter particles into two categories: undersized spatters (around 80 μ m) and oversized spatters (180 μ m or greater) in comparison to the base powder size of 60 μ m. Similarly, Anwar and Pham [17] investigated spatter distribution on the powder-bed and found spatter sizes from 90 μ m to 160 μ m across various zones in the build chamber. Young et al. [65] reported that agglomerated powder spatters averaged around 114 μ m, approximately four times larger than the base powder, while entrainment melting spatters, which are spatters that occur when powders, transported by a gas flow, undergo a process of melting and fusion as they pass through the laser heating region. averaged at 57 μ m. These uneven spatter sizes can lead to parts with uneven layer thickness resulting in defected parts. For

instance, Simonelli et al. [48] studied the effect of spatter sizes on the quality of printed parts. Their results showed that presence of spatter particles resulted in lower part quality due to inhomogeneous layer thickness.

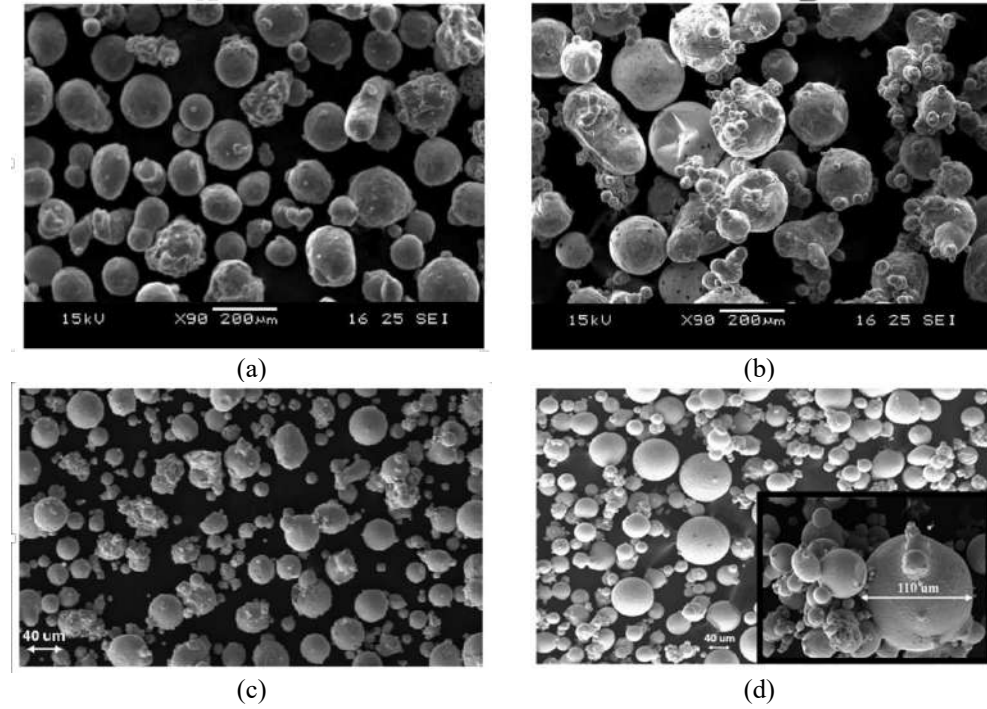


Figure 2.11: SEM analysis of (a) Fresh AlSi10Mg powder [42], (b) AlSi10Mg Spatter particles [42], (c) As-received Hastelloy X powder [6], and (d) Hastelloy X Spatter particles [6].

Table 2.1 summarizes the spatter size variations reported in literature. From Table 2.1, it was observed that 316L Stainless Steel was the most commonly studied material with varying sizes. This discrepancy in the particle sizes was a result of experimental data preferred for validations. For example, Zhang et al. [11] used 20 µm, 30 µm, 50 µm, and 70 µm spatter sizes for their simulation study. They chose these spatter sizes by utilizing the normally distributed experimental data [66]. Similarly, Alqaity [61] used 80 µm, 110 µm and 140 µm spatter sizes to simulate the effect of spatter sizes on their transport based on experimental studies [10], [17]. The choice of the experimental data used for validations led to the size differences observed in various works.

2.4.8 Particle Ejection Angle

The selection of spatter ejection angles primarily relies on experimental findings. For instance, Chien et al. [15] found that the mean spatter ejection angle for 50 randomly selected spatters was 35°, with a standard deviation of 15°. This specific ejection angle was subsequently employed in their simulation study. Likewise, Zhang et al. [11] utilized ejection angles ranging from 45° to 70°, based on the results from an experimental study of SS316L [66]. Table 2.1 shows the summary of the ejection angles as well as the spatter sizes used in simulation studies.

Table 2.1: Summary of spatter materials, sizes, and ejection angles used for gas flow and spatter simulations from the literature

Authors	Spatter Material	Spatter Size	Ejection Angle
Chien et al. 2021 [15]	316L Stainless steel	63 μm (mean)	35°
Zhang et al. 2020 [11]	316L Stainless steel	20 μm , 30 μm , 50 μm , and 70 μm	45° to 70°
Alquaity and Yilbas 2022 [8]	316L and AlSi10Mg	60 μm , 120 μm and 180 μm	45° and 70°
Zhang et al. 2019 [12]	AlSi10Mg, Ti64 and SS316L	20 – 80 μm	60°,90° and 120°

Alquaity 2021 [61]	AlSi10Mg	80 μm , 110 μm and 140 μm	20° and 40°
Philo et al. 2017 [16]	316L stainless steel	60-120 μm with an average of 90 μm	
Tzeng et al. 2020 [64]	Titanium alloy	20~80 μm	

2.5 Parameters Evaluated in Literature

This section will delve into the discussion of different machine parameters and their effects, as outlined in the reviewed literature. Inert gas flow parameters, including inlet flow rate, inlet height, inlet width, outlet height, and others, have been extensively examined in the literature to understand and optimize the flow dynamics within the LPBF chamber. Figure 2.12 provides a visual representation of these parameters along with their approximate locations.

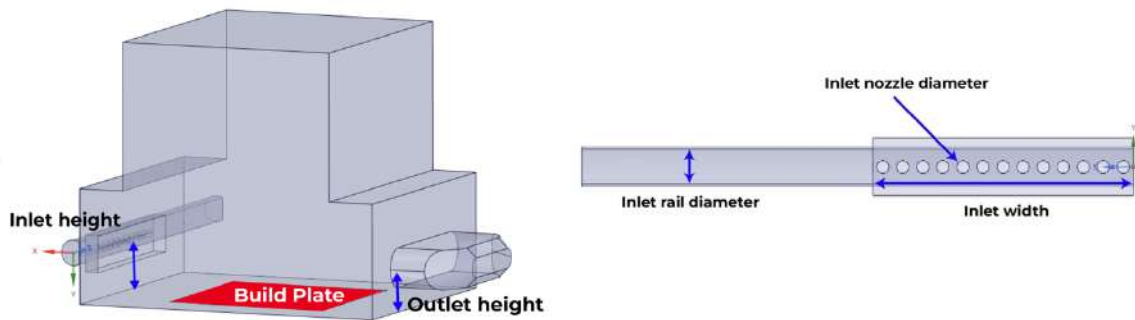


Figure 2.12: Inert gas flow parameters evaluated in literature

2.5.1 Gas Flow Rate

The gas flow rate exerts a substantial influence on spatter removal within the laser powder-bed fusion build chamber. Several studies have found that an increase in gas flow reduces the amount of spatter deposition on the build plate, as more spatter particles are propelled

towards the outlet [3], [13]. For instance, Zhang et al. [11] investigated the impact of three different flow rates (250 L/min, 500 L/min, and 750 L/min) on spatter distribution. They observed that at lower flow rates, most spatter tended to accumulate on the build plate due to the dominant influence of gravitational force over the drag force. As the gas flow rate increased, they noted shifts in spatter trajectories, with spatter particles being carried farther away from the build plate, thereby increasing the clearance rate (Figure 2.14). Likewise, Alqaity and Yilbas [8], conducted simulations at multiple flow rates to analyze the velocity profile under different extreme flow conditions. While they observed a reduction in spatter deposition on build plate at higher flow rates, their results indicated no significant difference in the velocity profiles between the two extreme flow rates (Figure 2.13).

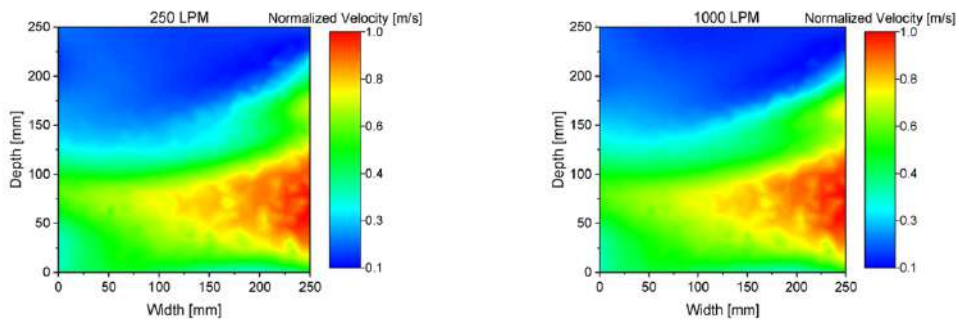
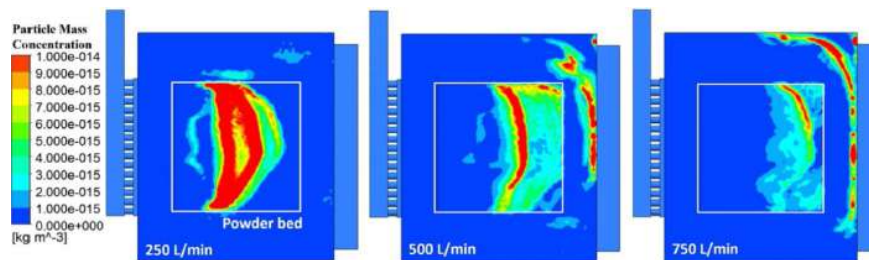


Figure 2.13: Velocity contours (center plane) at 250 LPM and 1000 LPM [8]



(a)

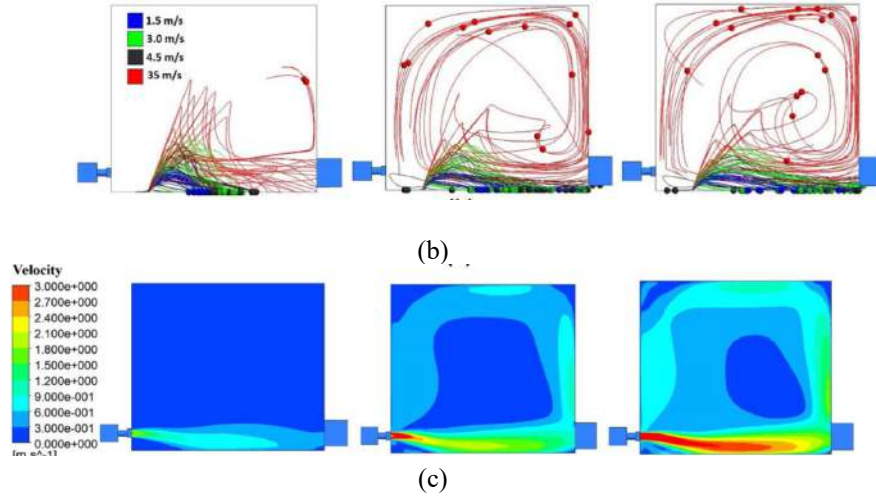


Figure 2.14: The effect of inlet gas flow rate on ejected particle distribution: (a) Re-deposited spatter particles concentration contour (b) Trajectories of spatter particles (c) Side-plane velocity contour [11]

2.5.2 Inlet Width

Zhang et al. [12] conducted a simulation study to explore the impact of inlet width on the flow field and velocity profile, examining three different widths: 225 mm, 250 mm, and 275 mm. They observed a subtle difference in the velocity profile (Figure 2.15). However, the largest inlet width (275 mm) led to a diminished gas velocity profile above the build area. An inlet width equal to the build plate width (250mm in this case) was suggested as the most effective solution. Similarly, Chen et al. [18], made modifications to the baseline design (Renishaw AM250) by augmenting the quantity of nozzles in the inlet width array. They reported a more even distribution of gas flow throughout the build chamber in the modified inlet width design compared to the initial design (Figure 2.15).

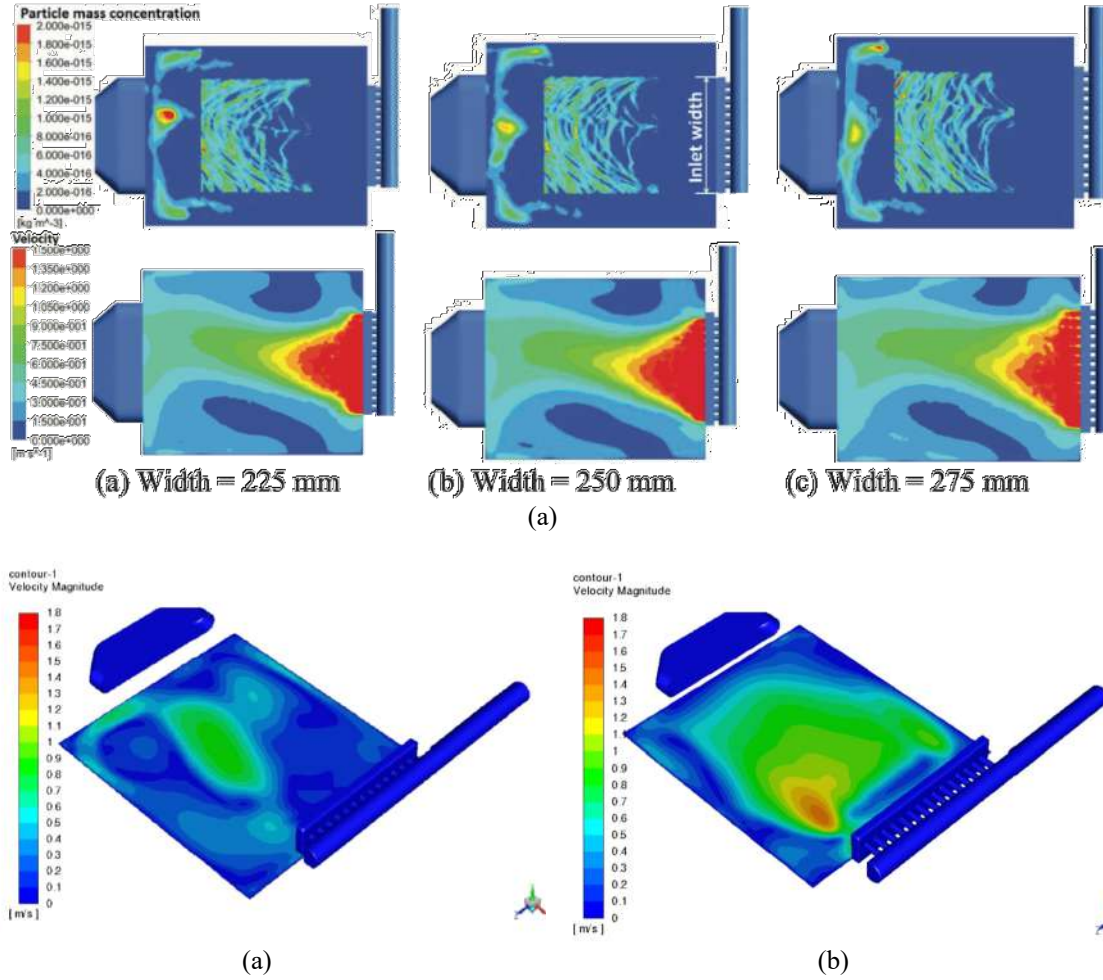


Figure 2.15: (a) Effect of inlet width on particle re-deposition and velocity [12] and velocity profile on a plane 3 mm above the build plate for (a) Baseline design [18] (b) Design with more nozzles, and reduced inlet height [18]

2.5.3 Inlet Height

The inlet height, as commonly defined in most studies [16], [18], refers to the vertical distance from the midpoint of the inlet nozzles to the build plate. In a simulation study, Zhang et al. [12] investigated the impact of inlet height on the velocity profile, considering three different heights: 50 mm, 67.5 mm (initial design), and 85 mm. Their findings revealed that a moderate inlet height of 67.5 mm provided the highest clear rate by effectively transporting a large number of spatters away from the build plate in comparison to the other inlet heights. (Figure 2.16). On the other hand, designs with a low inlet height

do not enable effective spatter removal as spatter particles experience highest velocities near the build plate (low height). Conversely, in cases with a high inlet height, the high gas velocity region may be too elevated to exert a substantial influence on the spatter particles. Similarly, Chen et al. [18] reported an increase in inert gas flow uniformity by reducing the inlet height and extending the nozzle length of the baseline Renishaw AM250 design. Likewise, Philo et al. [16] also observed a reduction in gas flow uniformity as the inlet height was increased, hence reducing spatter removal efficiency.

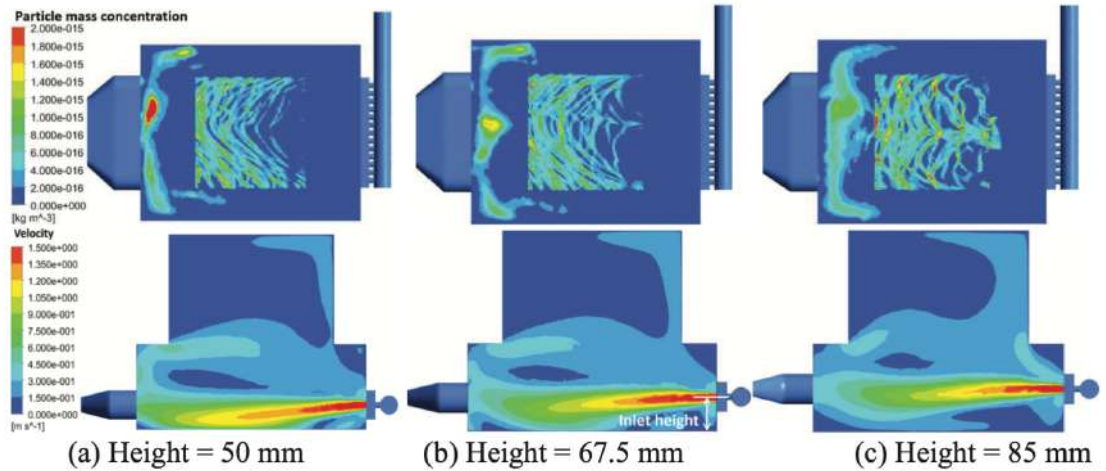


Figure 2.16: Effect of inlet height on particle re-deposition on the build plate and velocity [12].

2.5.4 Inlet Rail Diameter

The inlet rail diameter is defined as the diameter of the conduit through which the gas flows before entering the build chamber through the inlet nozzle as shown in Figure 2.12. Philo et al. [16] examined the impact of the inlet rail diameter on gas flow uniformity. They found that while enlarging the inlet rail diameter resulted in a reduction in gas flow uniformity, it led to an increase in the average flow velocity across the build area. This, in turn, contributed to a reduction in spatter concentration on the build plate.

2.5.5 Inlet Nozzle Diameter

Alquaity and Yilbas [8] explored various methods to enhance inert gas flow in the Renishaw AM250 by adjusting machine parameters. They recommended improving gas flow by partially obstructing the current nozzle design. In their simulations, they reduced the inlet nozzle diameter from 12 mm to 6 mm, resulting in a 60% increase in gas velocity over the build plate. This high velocity resulted in higher spatter removal. Likewise, Philo et al. [16] observed that enlarging the inlet nozzle diameter led to a decrease in flow uniformity and average flow velocity.

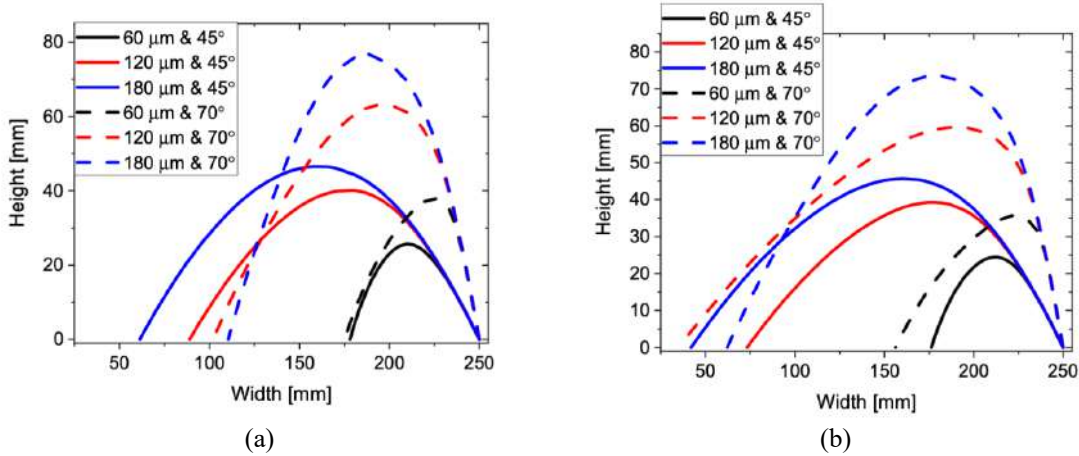


Figure 2.17: Effect of reduced inlet nozzle diameter on spatter trajectories (a) Initial design (12mm diameter) and (b) Modified design with 6mm diameter [8]

2.5.6 Outlet Height

In the study conducted by Zhang et al. [11], two regions with concentrated spatter were identified. The first region was situated within the build area, while the second was in close proximity to the outlet and impeded the flow of spatter particles. This resulted in the accumulation of spatter particles near the outlet, consequently elevating the spatter concentration. Their findings indicated that lowering the outlet height facilitated the transport of spatter particles away from the build chamber, thereby reducing the spatter

concentration around the outlet. Similarly, Philo et al. [16] observed a decrease in inert gas flow uniformity as the outlet height increased. They also noted a reduction in spatter clear rate with an increase in outlet height.

2.5.7 Spatter Size and Ejection Angle

The effect of ejection angle is sparsely reported in the literature. Alquaity and Yilbas [8] investigated the impact of two different ejection angles (45° and 70°) on three varying spatter diameters (Figure 2.18). Their findings revealed that as the diameter of the spatter particles increased, those ejected at 45° exhibited a longer range, being transported further away from the point of ejection compared to spatters ejected at 70° .

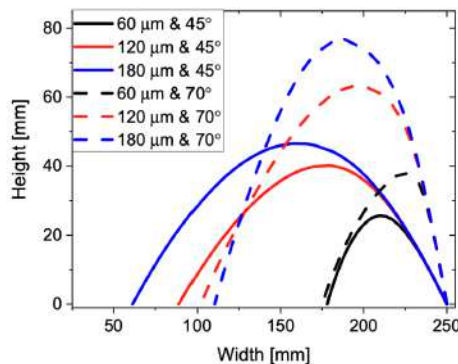


Figure 2.18: Trajectories of spatters ejected at different ejection angles [8]

2.5.8 Spatter Material

The material properties of spatter particles also play a crucial role in the spatter clear rate [17]. Zhang et al. [12] conducted a comparative study to analyze the effect of different spatter materials on spatter transport within the build chamber. They observed a higher removal rate for lighter materials, with AlSi10Mg exhibiting a clear rate of 69.4%, while Ti64 and SS316L showed rates of 68.3% and 60.4% respectively. **Error! Reference source not found.** provides a summary of the parameters investigated in literature. Despite the significance of process parameters and their impact on spatter removal, only a limited

number of authors have delved into the effects of these parameters on inert gas flow and spatter trajectories.

CHAPTER 3

METHODOLOGY

3.1 Materials Simulated

In this study, three distinct materials; aluminum alloy AlSi10Mg, stainless steel 316L, and Hastelloy X were employed. This choice allowed for an investigation into the impact of inert gas flow on materials with varying properties. The respective densities of these materials are as follows: AlSi10Mg - 2700 kg/m³, SS316L - 7950 kg/m³ and Hastelloy X - 8220 kg/m³. AlSi10Mg (Table 3.1) is widely used in the aerospace, automotive, chemical, and food industries [67], [68]. The incorporation of magnesium into the Al-Si alloy enables the precipitation of Mg₂Si, thereby reinforcing the matrix without adversely affecting other mechanical properties.

Elemental composition of stainless steel 316L is shown in Table 3.1. Stainless steel 316L, a widely adopted alloy in laser powder-bed fusion, owes its popularity to its robustness and widespread use in industries spanning biomedical, aerospace, automotive, and nuclear sectors [69]. Hastelloy X, described in Table 3.1, is a nickel-based superalloy that has been recognized for its remarkable oxidation resistance as well as its strength at high temperatures. This unique combination of properties positions Hastelloy X as a vital material in gas turbine engines for combustion zones and the chemical processing industry [70], [71].

Table 3.1: Common alloying elements used for spatter materials used in this study (AlSi10Mg, SS316L, Hastelloy X) [68], [72], [73]

AlSi10Mg							
Alloying element	Al	Si	Cu	Mn	Mg	Zn	Fe
wt%	Bal.	9-11	<0.1	0.05	0.45-0.6	0.05	<0.55
SS316L							
Alloying element	Fe	Cr	Ni	Mo	Mn	Si	Cu
wt%	Bal.	17.2	8.97	2.13	1.03	0.77	<0.48
Hastelloy X							
Alloying element	Ni	Cr	Fe	Mo	W	Co	Si
wt%	Bal.	21.75	18.5	9	0.6	1.5	<1

3.2 Modelling Framework Simulated

In this study, CFD was employed to obtain the velocity profile of the inert gas (Argon) in the LPBF build chamber. The interaction between the Argon flow and the ejected spatters from the build plate was simulated using the DPM. This approach is widely recognized as the most common method for simulating spatter trajectories, as detailed in Section 2.4.5.2. The gas flow and spatter trajectories within the Renishaw AM250 chamber (Figure 3.1) were simulated using the Ansys Fluent 2022 R2. This software has been utilized in a substantial portion, approximately 72%, of the literature reviewed, as discussed in Section 2.4.1.

3.2.1 Computational Fluid Dynamics (CFD)

This study focused on analyzing the inert gas flow field within the LPBF build chamber, primarily using CFD simulations. Similar approaches have been adopted in previous researches for gas flow simulations as mentioned in Section 0. These simulations utilize the Eulerian-Lagrangian modeling technique, which employs principles of mass and

momentum conservation to calculate the flow field. The mass and momentum conservation equations (Section 0) are gives as:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{Equation 3.1}$$

$$\rho u_i \frac{\partial u_j}{\partial x_i} = - \frac{\partial p}{\partial x_j} + \mu \frac{\partial^2 u_j}{\partial x_i \partial x_i} \quad \text{Equation 3.2}$$

where ρ represent the density of the inert gas, u_j represents the velocity vector, p represents the static pressure, μ is the dynamic viscosity, x_i is the spatial vector, and t is the time.

3.2.2 Discrete Phase Model (DPM)

The DPM is widely embraced for simulating spatter ejection within the build chamber (Section 0) and was chosen to model the spatter particles. The force balance equation and the drag force per unit mass (F_D) are shown below [8]:

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u} - \vec{u}_p) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} \quad \text{Equation 3.3}$$

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D Re_{rel}}{24} \quad \text{Equation 3.4}$$

3.2.3 Turbulence Model

In this study, the flow was assumed to be steady, incompressible, and turbulent. Philo et al. [16] identified the gas flow in the build chamber as turbulent, with a Reynolds number on the order of 4000, placing the flow in the turbulent or transitional regime. The selected turbulence model was the realizable $\kappa - \epsilon$ model, which was recognized as the most

appropriate model for simulating gas flow in the LPBF chamber (Section 0). The governing equations for turbulent kinetic energy (k) and kinetic energy dissipation rate (ϵ) (Section 0) are expressed as:

$$\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + G_b - \rho \epsilon \quad \text{Equation 3.5}$$

$$\frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_i} \right] + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} \quad \text{Equation 3.6}$$

where u_i represents the fluid velocity component, μ_t represents the eddy viscosity, G_k corresponds to the generation of turbulent kinetic energy attributed to mean velocity gradients, G_b represents the turbulence kinetic energy generation by buoyancy, σ_k and σ_ϵ represent the turbulent Prandtl numbers for k and ϵ respectively, and $C_{1\epsilon}$, C_2 , and $C_{3\epsilon}$ are constants with default values specified for the Realizable k- ϵ model.

3.3 Numerical Model Configurations

3.3.1 Geometry

This study involved simulating spatter generation and transport within a Renishaw AM250. The Renishaw AM250 geometry used in this work was created using Solidworks®. Figure 3.1 provides a schematic of the Renishaw AM250 LPBF machine utilized in this study.

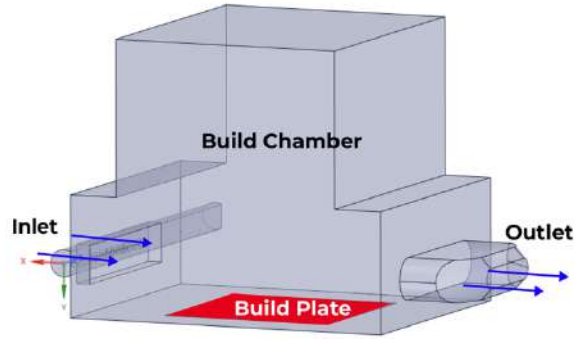


Figure 3.1: Renishaw AM250 schematic.

3.3.2 Meshing

In this study, a fine mesh was applied in proximity to the inlet and outlet regions. In consideration of the sharp gradients adjacent to the wall boundaries, inflation layers (comprising 5 layers with a growth rate of 1.1) were implemented. Conversely, areas with less pronounced gradients received a coarser mesh to expedite computations. Additionally, a mesh independence study with six varied mesh sizes was conducted to ensure the selection of an optimal mesh.

3.3.3 Simulation Setup

The Renishaw AM 250 LPBF machine uses a gas flow rate of 250 LPM. Therefore, the inlet velocity was set at 250 LPM. In order to achieve this, the velocity inlet boundary condition was used with a velocity magnitude of 4.3 m/s, while outflow was assigned as the outlet boundary condition (Table 3.2). To reduce computational costs, a trap boundary condition was applied to all walls, including the build plate. This condition was implemented to prevent spatters from rebounding after impacting the walls or build plate.

Table 3.2: The applied boundary conditions for this simulation study.

Boundary Conditions	Type	Velocity Magnitude (m/s)
Inlet	Velocity Inlet	4.3039
Outlet	Outflow	-

3.3.4 Spatter Particles Ejection Setup

As previously mentioned, this study simulated spatters of three different materials (AlSi10Mg, SS316L, and Hastelloy X) with three distinct spatter sizes (60 μm , 120 μm , and 180 μm). These selections were made to encompass the majority of spatter sizes documented in the literature as detailed in Section 2.4.7. The particles were ejected from six distinct locations on the build plate both in the flow and opposite the inert gas flow direction. Figure 3.2a illustrates the ejection locations considered when the spatters were ejected in the argon gas flow direction (P1, P2, P3, P4, P5, and P6), while Figure 3.2b depicts the ejection locations when the spatters were ejected in the opposite direction (P4, P5, P6, P7, P8, and P9). It is important to note that, in both scenarios, P4, P5, P6 denote particle locations positioned in the middle of the build plate.

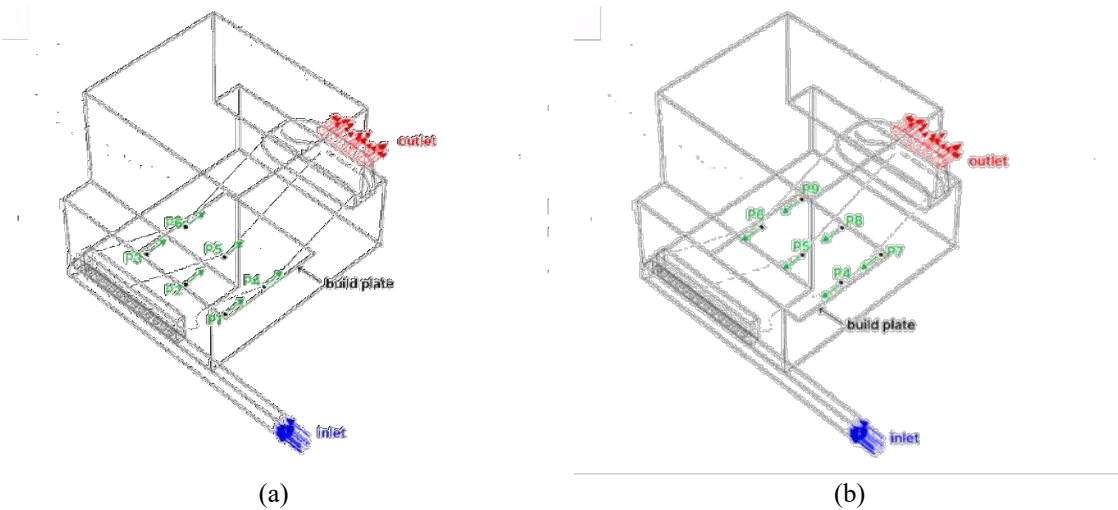


Figure 3.2: Ejection locations used in this study (a) The scenario where spatters are ejected in the direction of the argon gas flow and (b) The scenario where spatters are ejected in the direction opposing the argon gas flow.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Grid Independent Test

Grid independence was assessed using six distinct meshes (Table 4.1 and Figure 4.1). Each mesh was chosen to successively decrease in size, and employed 2000 iterations to ascertain the optimal mesh size. The average output velocity from each mesh served as the criteria for mesh independence. The outcomes presented in Table 4.1 demonstrate that there were no notable alterations in the average output velocity once the mesh size exceeded 6.8 million elements, corresponding to a mesh size of 2.15 mm. As such, an average mesh size of 2.15 mm was implemented for this study.

Table 4.1: Results obtained from the grid independent test involving six mesh sizes

Element Size [mm]	Mesh Nodes	Mesh Elements	Outlet-Velocity [m/s]
10.0	879,899	4,356,343	1.0037
7.5	894,633	4,403,495	1.0260
5.0	947,196	4,549,367	1.0300
2.5	1,399,112	6,130,533	1.0374
2.15	1,712,604	6,870,495	1.0435
2.0	1,867,003	7,370,037	1.0433

While average velocity offers a comprehensive assessment of grid independence, it may not detect localized mesh disparities. Hence, the study also examined average velocity

across the build plate. Figure 4.1 illustrates the average velocity profile at various locations on the build plate. Examining the velocity profile along the left edge (Position 0 m and 0.25 m) using different mesh sizes. It was evident that results obtained with a 2.15 mm mesh closely matched those from a 2 mm mesh as shown in Figure 4.1. Moreover, velocity trends across the build plate were consistently replicated between the 2.15 mm and 2 mm mesh sizes. Consequently, a mesh element size of 2.15 mm was adopted for subsequent simulations.

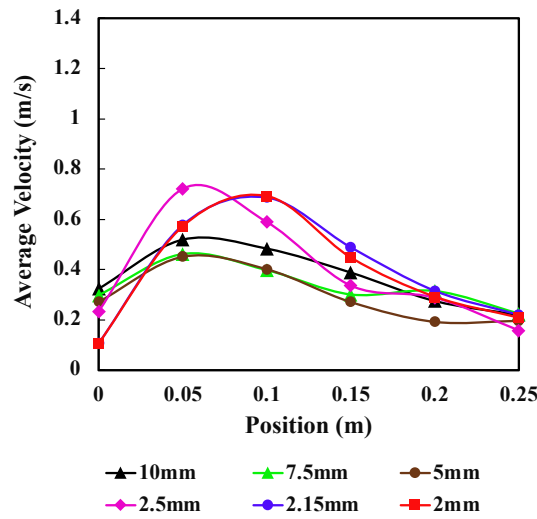


Figure 4.1: Average gas flow velocity along the left edge of the build plate with various mesh sizes

4.2 Model Validation

Validating a computational model is a critical prerequisite for drawing meaningful conclusions. It serves to establish the credibility of simulation outcomes, ensuring that they align with experimental data. In this study, model validation involved comparing the simulation velocity contour of argon gas along the center plane with experimental findings [16]. The results indicated a congruence in both velocity magnitude and profile (Figure 4.2) with the experimental data [16]. Consequently, it can be affirmed that the proposed

model has been successfully validated and can be relied upon for simulating the impact of inert gas flow within LPBF build chambers.

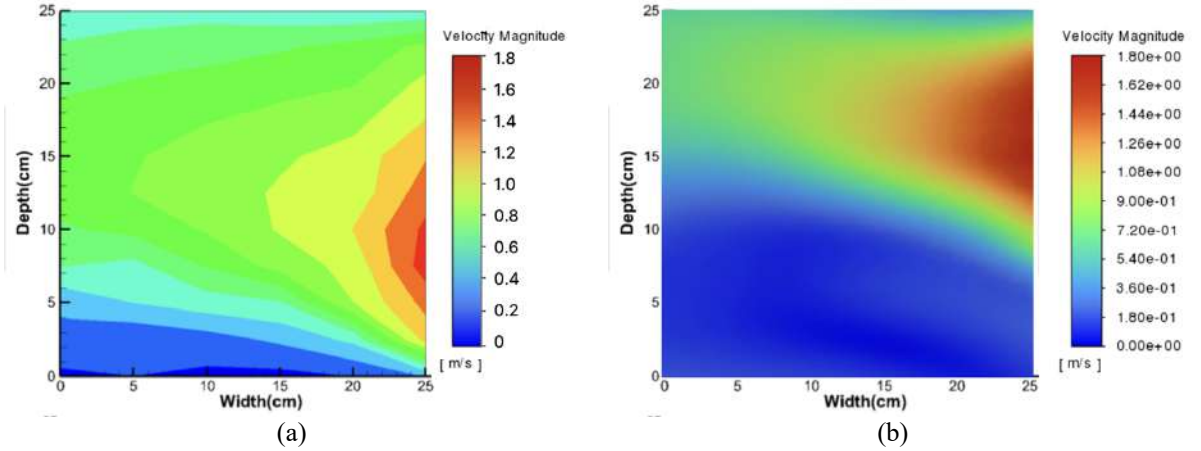


Figure 4.2: Validating the model by comparing simulated velocity contour over the build plate to the experimental velocity contour (a) Experimental center plane [16] and (b) Simulation center plane

4.3 Argon Flow Field

Argon gas is introduced into the build chamber to establish an inert atmosphere during the manufacturing process. Additionally, argon gas flow plays a pivotal role in spatter removal, as substantiated by numerous studies [10], [11]. Thus, an in-depth examination of argon flow within the build chamber is warranted. Figure 4.3a illustrates the velocity profile 67.5 mm above the build plate (inlet height in Figure 3.1) in the center plane. Evidently, inert gas flow non-uniformity was observed across the build plate which can be attributed to the inlet geometry. Consequently, areas with lower velocity might experience heightened spatter depositions, since the gas velocity is insufficient for propelling spatters away from the build plate. Figure 4.3b illustrates the downward inclination of gas flow, a phenomenon known as the Coanda effect, as it flows through the build chamber. This effect arises from pressure differences surrounding the incoming gas flow stream and holds significance in the process of spatter transport [11]. Coanda effect can redirect the ejected spatters back

towards the build plate, particularly for smaller and lighter spatters. Consequently, this raises the likelihood of spatter deposition on the build plate.

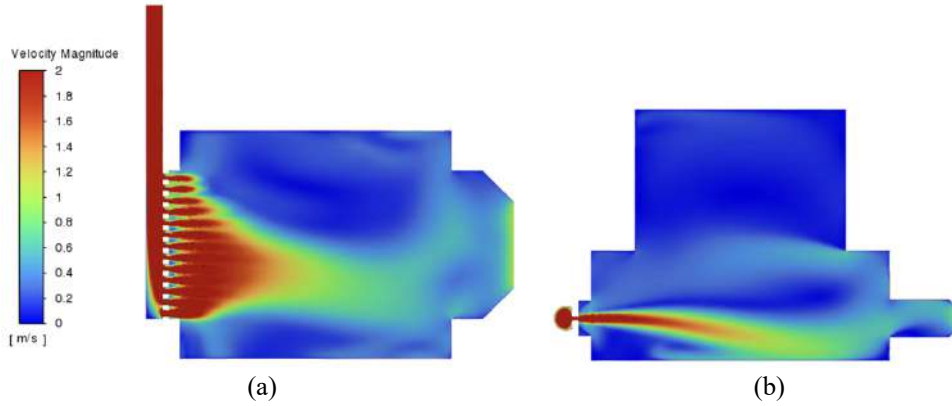


Figure 4.3: Velocity contour (a) Centre plane, 67.5mm above build plate (b) XY plane

Simulation results in Figure 4.4 delineate the recirculation zone within the build chamber across three XY planes corresponding to spatter ejection locations in this study. Figure 4.4a illustrates the plane corresponding to P1, P4, P7 while Figure 4.4b-c depicts results corresponding to (P2, P5, P7) and (P3, P6, P9) respectively. Although all three planes exhibit a similar pattern, it's noteworthy that the recirculation zones on the right (Figure 4.4a) and left edges (Figure 4.4c) of the build plate are more pronounced compared to the center plane. While gas flow velocity in the recirculation zone is lower compared to the inlet velocity, these zones can exert a significant influence on spatter removal, particularly for small-sized particles of lightweight materials. When small-sized spatters of light materials are ejected in the flow direction and at high ejection angles, they could be redirected back to the build plate upon reaching the recirculation zone. It's pertinent to observe that the plane furthest from the inlet pipe (Figure 4.4c) experiences higher velocities compared to the other planes due to lower turbulence. This, in turn, impacts particle ejections from these locations (P3, P6, P9).

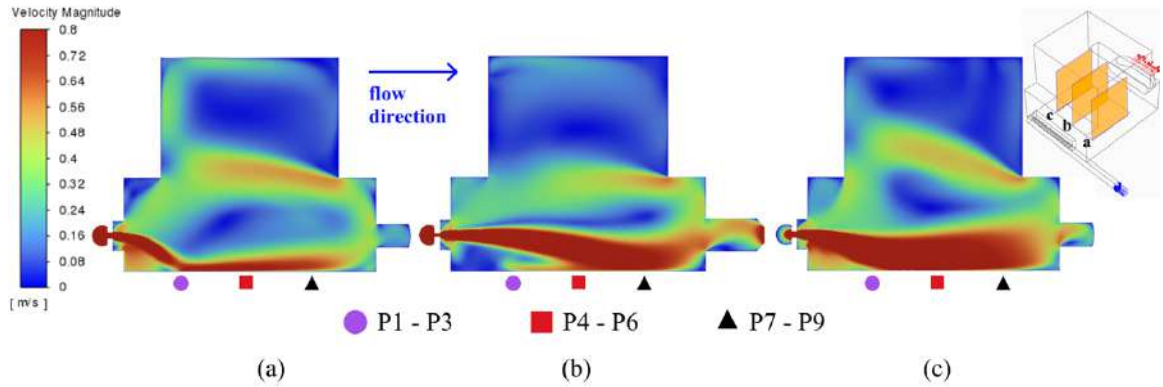


Figure 4.4: Velocity distribution in the build chamber showing the recirculation zone (a) Right edge of the build plate (ejection location P1, P4, and P7) (b) Center of the build plate (ejection location P2, P5, and P8) (c) Left edge of the build plate (ejection location P3, P6, and P9)

4.4 Spatter Trajectories

The presence of regions with low flow velocities as seen in Figure 4.3 highlights areas that are more susceptible to spatter deposition. Consequently, it is imperative to investigate the trajectories of spatter particle ejection across the entire build plate. It is well known that different materials affect the spatter generation and size. In addition, spatter particles generated during LPBF follow various sizes as discussed previously (Section 3.3.4). Finally, spatter particles are generated at varying angles, and their trajectories may align with or opposite the inert gas flow. Hence, it is imperative to study the spatter material and relative trajectories of spatter particles with different sizes, location, ejection angles and ejection direction. In this section, spatter particles of AlSi10Mg, Stainless Steel 316L, and Hastelloy X, with sizes ranging from 60 μm to 180 μm , were examined. These particles were also ejected from various locations on the build plate at different angles (20°, 45°, and 70°) in both the direction of and against the argon flow. It is pertinent to mention that only trajectories within the build chamber are presented.

4.4.1 AlSi10Mg Spatters

a) 60 μm Spatter Particles

i. Spatter Particles Ejected in the Direction of Argon Gas Flow

Figure 4.5a-c illustrate the trajectories of spatter particles ejected at 20°, 45°, and 70° respectively, from various locations on the build plate. For spatters ejected at a 20° angle (Figure 4.5a), all 60 μm AlSi10Mg particles were observed to be transported beyond the build plate. This can be attributed to the weight of the AlSi10Mg particles and the high ejection velocity resulting from constant momentum.

Similarly, for spatters ejected at 45° (Figure 4.5b), only particles ejected from P1 (Figure 3.2a) were deposited on the build plate. It is noteworthy that as the spatters descend, they tend to alter their direction in the region of high velocity, which is observed around 67.5 mm above (inlet height) the build plate (Figure 4.1b). Once at this height, the argon flow carries the spatters away from the build chamber. The inconsistencies in flow behavior (Figure 4.3) cause positions P1, P2, and P3 to exhibit similar behavior. However, only particles ejected from P2 and P3 are found outside the build plate.

Lastly, for spatters ejected at 70°, it was observed that spatter particles ejected from P2 and P3 were deposited on the build plate (Figure 4.5c). This is because at 70°, the spatter particles tend to cover shorter distances compared to other ejection angles. Consequently, 60 μm spatter sizes ejected at 70° have a higher likelihood of depositing on the build plate compared to other ejection angles examined in this study. Additionally, the high ejection angle allows the spatter to reach the recirculation zone in the build chamber. In this zone (Figure 4.5a), the spatters are blown in the opposite direction of the flow and subsequently carried back onto the build bed. It is worth noting that the gas flow velocity in the

recirculation zone (0.75 m/s) is lower than the average velocity on the build plate (approximately 1.5 m/s). However, this low velocity suffices to displace the small-sized ($60\text{ }\mu\text{m}$) and lightweight (AlSi10Mg) spatter particles. Furthermore, velocities differ across the build plate, as depicted in Figure 4.4. Consequently, only particles ejected from P2 and P3 are reintroduced to the build plate, owing to the relatively high gas flow velocities in this region. As a result, it is anticipated that this low recirculation velocity should not affect the spatter particles of heavier materials such as SS316L and Hastelloy X.

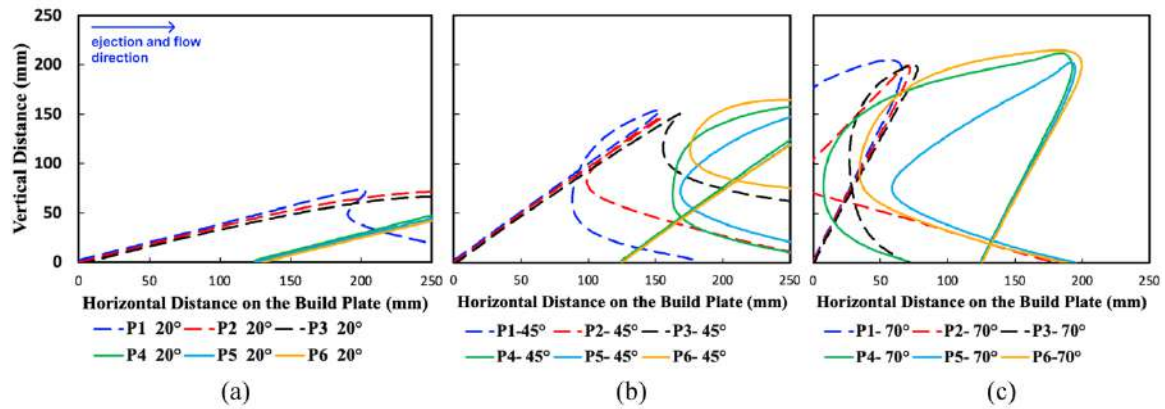


Figure 4.5: Trajectories of $60\text{ }\mu\text{m}$ AlSi10Mg spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70°

ii. Spatter Particles Ejected in the Direction of Argon Gas Flow

Spatter particles were also ejected in the direction against the inert gas flow for all ejection angles. At a 20° angle, it was observed that only particles ejected from positions P4 (located in the middle of the build plate) and P8 (at the edge of the build plate) were deposited outside the build plate. Other ejected particles were deposited on the build plate due to their low weight (Figure 4.6a).

Furthermore, at a 45° ejection angle, spatter particles ejected from P4, P6, and P8 were deposited outside the build plate, while those from positions P5, P7, and P9 were deposited on the build plate (Figure 4.6b). The spatters ejected from P5 travel the farthest after their

reversal of direction due to higher inert gas velocities in the center of the build plate (corresponding to P5). The spatters ejected at the edge of the build plate also exhibit a similar trajectory at 45° and 20° ejection angles.

Finally, at 70°, only particles ejected from P4 and P7 (along the right edge of the build plate as shown in Figure 4.4a) were transported away from the build plate. The gas flow velocity along this edge was lower compared to the other ejection sites, as indicated in Figure 4.4a. This low velocity along this region was insufficient to alter the trajectories of these particles, resulting in their transportation away from the build plate. However, other spatter ejections were deposited on the build plate, as the gas flow velocities in these regions significantly influenced the spatter trajectories (Figure 4.6c).

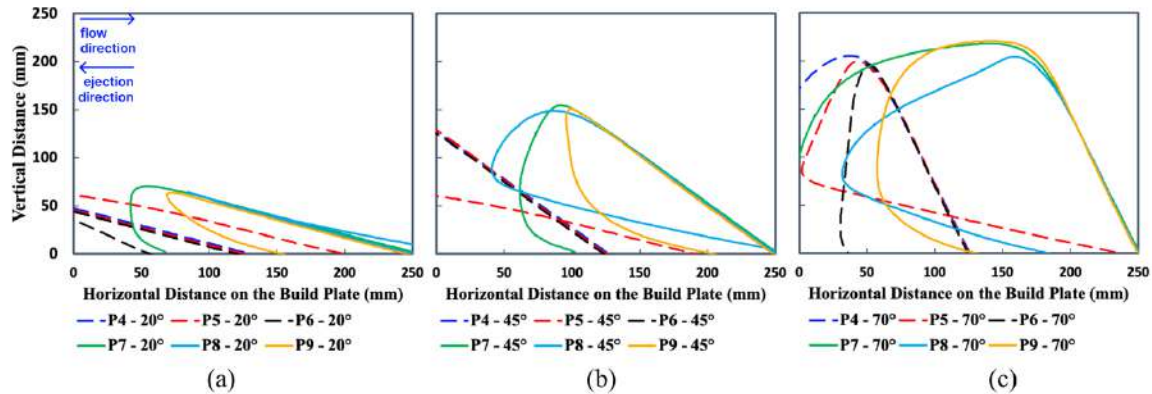


Figure 4.6: Trajectories of 60 μm AlSi10Mg spatters ejected at various ejection angles in opposite direction to the flow (a) 20° (b) 45° (c) 70°

b) 120 μm Spatter Particles

i. Spatter Particles Ejected in the Direction of Argon Gas Flow

Figure 4.7a illustrates the behavior of 120 μm spatters at a 20° ejection angle. The larger size reduces their ejection speed, decreasing the likelihood of exiting the build plate. At a 20° angle, particles from the edge of the build plate (P1, P2, and P3) were deposited on it, while particles from the middle ejections (P4, P5, and P6) were transported beyond it.

Furthermore, with a 45° ejection angle, almost all the spatters were deposited outside the build plate, except for those ejected from P1 (Figure 4.7b). Here, the gas flow velocity was lower, preventing the particles from being pushed farther away from the build plate. Finally, at a 70° ejection angle, spatters from the edge of the build plate (P1, P2, and P3) were transported beyond the build plate. Analysis of the particle ejections from the middle of the build plate show that only the spatters ejected from position P4 were deposited due to the lower gas flow velocity in this region, while P5 and P6 ejections were deposited outside the build plate (Figure 4.7c). Comparing all ejection angles, it was evident that spatters ejected at a 45° angle traveled the longest distance and exhibited the highest spatter removal.

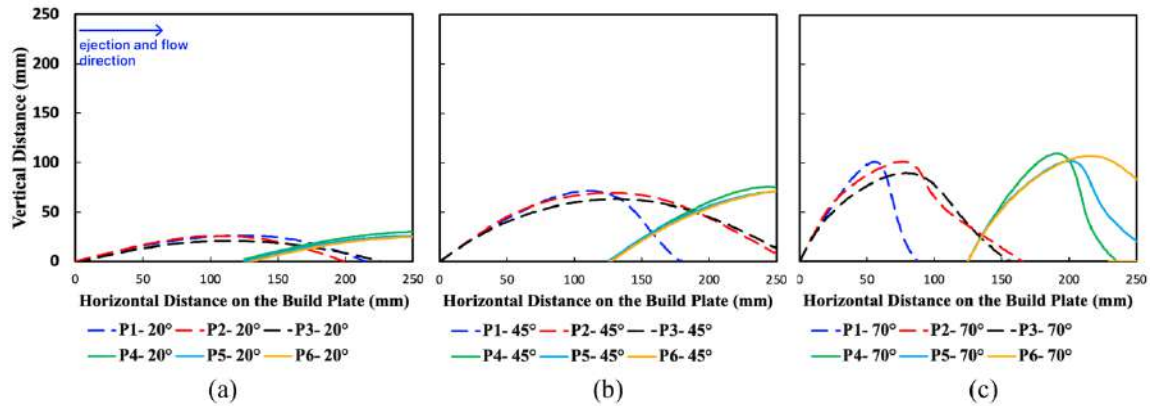


Figure 4.7: Trajectories of $120\ \mu\text{m}$ AlSi10Mg spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70°

ii. Spatter Particles Ejected in the Direction of Argon Gas Flow

At a 20° ejection angle, only the spatters ejected from P5 were deposited outside the build plate, while others landed on it (Figure 4.8a). This is in contrast to the behavior of $60\ \mu\text{m}$ spatters, where deposition on the build plate was influenced by changes in spatter trajectories due to gas flow velocity. Although gas flow velocity had minimal impact on spatter deposition in this case, the larger spatter size significantly reduced their range.

Furthermore, at a 45° ejection angle, it was observed that regardless of their ejection position, all spatters were deposited on the build plate (Figure 4.8b). Finally, at a 70° ejection angle, all spatters ejected from the middle of the build plate (P4, P5, and P6) were deposited on the build plate. Only P7, among the edge ejections (P7, P8, and P9), was deposited on the build plate due to the low gas flow velocity in this region, which was insufficient to transport the particles away from the build plate (Figure 4.8c).

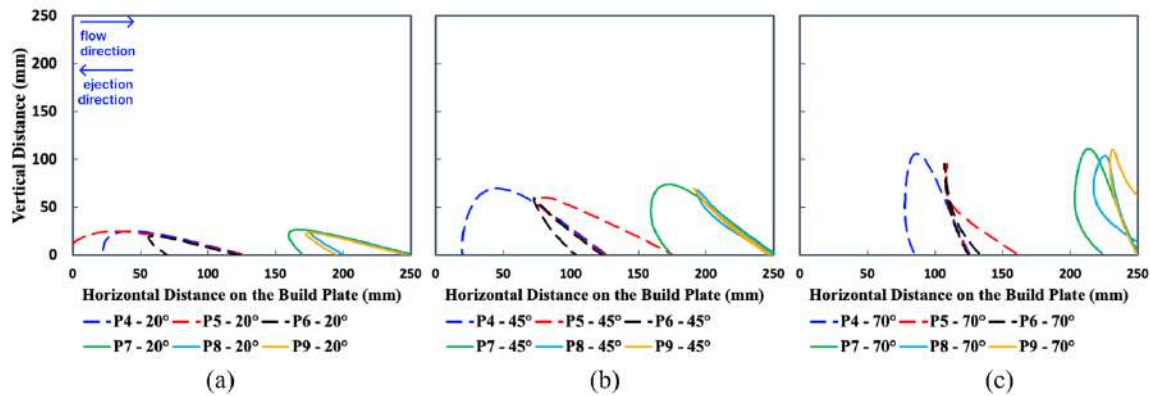


Figure 4.8: Trajectories of $120\ \mu\text{m}$ AlSi10Mg spatters ejected at various ejection angles in opposite direction to the flow (a) 20° (b) 45° (c) 70°

c) $180\ \mu\text{m}$ Spatter Particles

i. Spatter Particles Ejected in the Direction of Argon Gas Flow

Figure 4.9 depicts the trajectories of $180\ \mu\text{m}$ spatter particles for various ejection angles and locations. These larger spatter sizes, at $180\ \mu\text{m}$, possess more weight, leading to shorter travel distances and predominantly resulting in deposition on the build plate. At a 20° ejection angle, all ejected spatters were deposited on the build plate. Their higher weight, compared to the $60\ \mu\text{m}$ and $120\ \mu\text{m}$ spatters, limited their travel range (Figure 4.9a). Furthermore, at a 45° ejection angle, all spatters were deposited on the build plate, except those ejected from P1 and P4 (Figure 4.9b). The size of the spatters prevented them from traveling beyond the build plate for center and edge ejections. Finally, at a 70° ejection

angle, similar to the observation at 45° , all spatters were deposited on the build plate (Figure 4.9c).

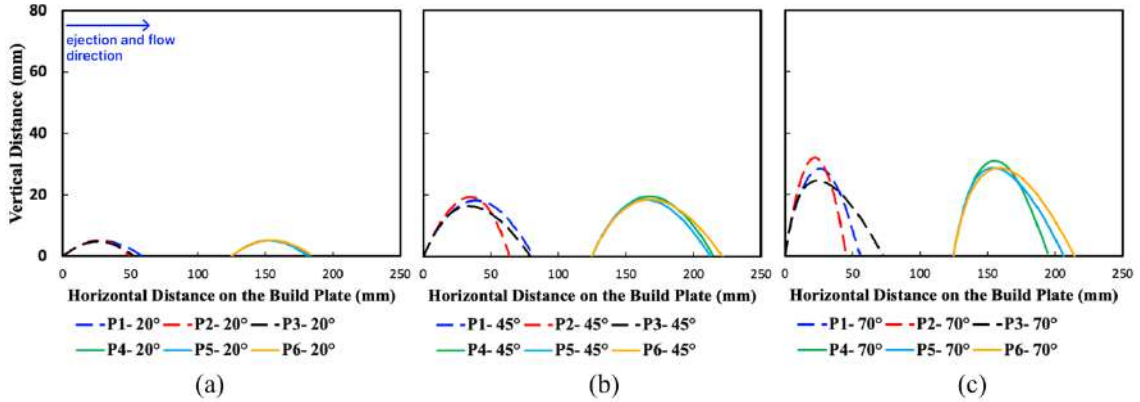


Figure 4.9: Trajectories of 180 μm AlSi10Mg spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70°

ii. Spatter Particles Ejected in the Direction of Argon Gas Flow

The 180 μm spatter particles ejected at 20° and 45° against the flow direction, were observed to deposit on the build plate. However, at 70°, only those ejected at the middle of the build plate (P4, P5, and P6) were deposited on the build plate, while those ejected at the edge of the build plate (P7, P8, and P9) were transported away from the build plate (Figure 4.10c). This phenomenon can be attributed to the high ejection angle of 70°. At this angle, the spatters tend to cover longer vertical distances, bringing them closer to the region of higher flow velocity. This results in removal of spatters ejected from the edge of the build plate (Figure 4.10c).

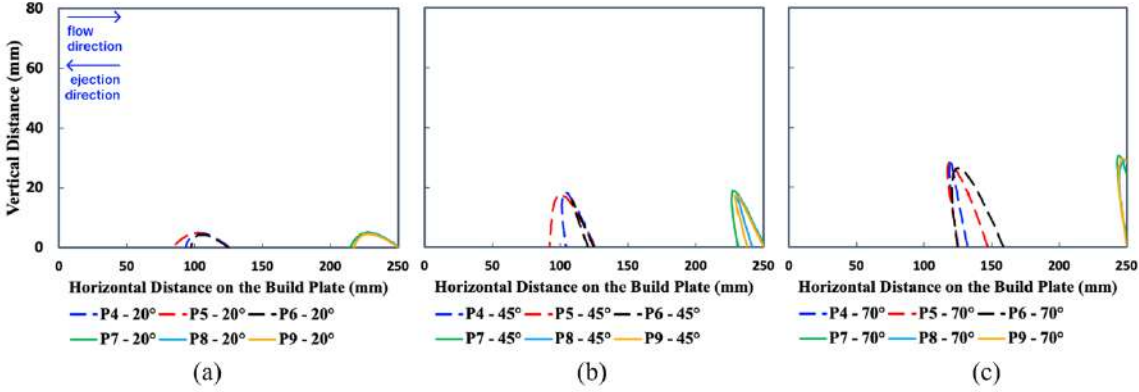


Figure 4.10: Trajectories of 180 µm AlSi10Mg spatters ejected at various ejection angles in opposite direction to the flow (a) 20° (b) 45° (c) 70°

In summary, lighter AlSi10Mg particles were easily transported out of the build area due to their weight and high ejection speed. However, for smaller spatters ejected at higher angles, some reached the recirculation zone where the lower gas flow velocity guided them back to the build plate, as seen with 60 µm spatters ejected at 70° (Figure 4.5c). A summarized depiction of particle landings on the build plate for all ejection angles, spatter sizes, and flow directions is presented in Figure 4.11. It was noted that all 180 µm spatter particles ejected in the flow direction for all ejection angles were deposited on the build plate. This aligns with published results where larger spatters were deposited closer to the ejection point while smaller particles were carried further downstream [17]. Additionally, spatters ejected from positions more distant from the inlet (middle and further corner) had a higher likelihood of being deposited outside the build plate due to higher flow velocities as shown in Figure 4.4. Conversely, the recirculation flow carried particles back to the build plate, as seen in Figure 4.5c with P2 and P3 spatters being deposited due to recirculation flow. Notably, a higher number of 60 µm AlSi10Mg particles were deposited on the build plate compared to other materials of the same size.

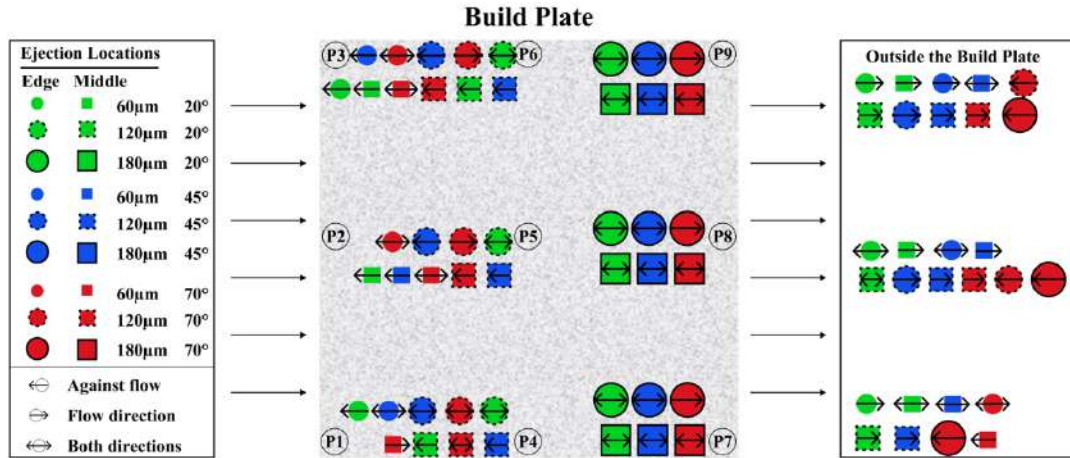


Figure 4.11: Schematic illustrating the landing locations (both on and off the build plate) of AlSi10Mg spatters. The circular shape is indicative of spatters ejected from the edges (P1, P2, P3, P7, P8, and P9), while the square shape denotes ejections originating from the middle of the build plate (P4, P5, and P6).

4.4.2 Stainless Steel (SS) 316L Spatters

a) 60 μm Spatter Particles

In this study, SS316L spatter particles were ejected both in and against the flow direction. The trajectories of spatter particles in and against the flow direction are shown in Figure 4.12a-c and Figure 4.12d-f respectively. Due to their small size and high velocity, particles ejected in the flow at 20° were carried away (Figure 4.12a). Additionally, all the particles ejected at 45° and 70° traveled longer distances and were transported beyond the build plate (Figure 4.12b & c). The high ejection velocity of small spatters, along with the gas flow velocity in the recirculation zone, couldn't provide enough reverse flow to guide these spatter particles onto the build plate.

Results from particles ejected against the flow showed that all spatter particles left the build plate region, and the inert gas flow had negligible effect on the particle trajectories. This trend was consistent for particles ejected at 20° (Figure 4.12d) 45° (Figure 4.12e), and 70° (Figure 4.12f).

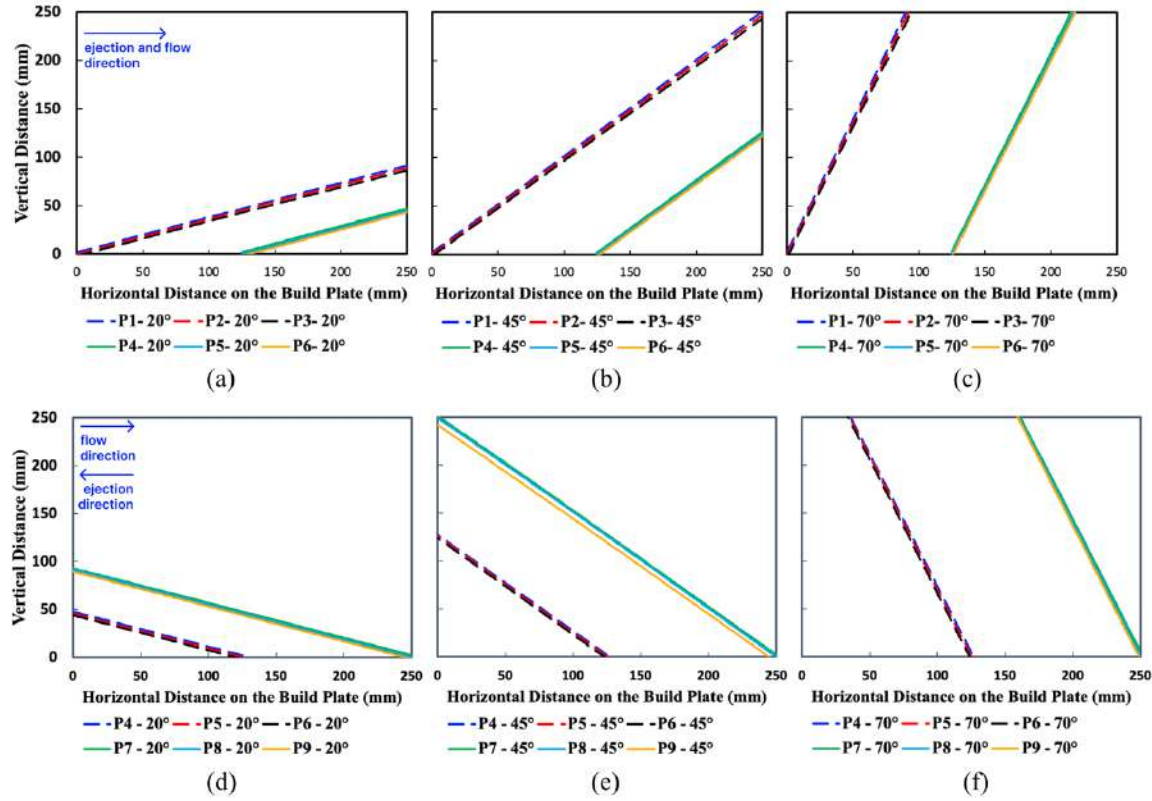


Figure 4.12: Trajectories of 60 μm Stainless steel 316L spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70° and in opposite direction to the flow (d) 20° (e) 45° (f) 70°

b) 120 μm Spatter Particles

i. Spatter Particles Ejected in the Direction of Argon Gas Flow

All 120 μm SS316L spatters ejected at 20° in the same direction as the gas flow were transported beyond the build plate (Figure 4.13a). Similarly, all spatters ejected at 45° traveled further away from the build plate (Figure 4.13b). Notably, spatters ejected at a 45° angle were observed to travel a greater distance compared to those ejected at other angles. Lastly, spatters ejected at a 70° angle from the edge of the build plate (P1, P2, and P3) were deposited on the build plate, owing to the high ejection angle. In this scenario, it was observed that the spatters covered a greater vertical distance in comparison to the horizontal

distance. Conversely, particles ejected from the middle of the plate (P4, P5, and P6) were all deposited outside the build plate (Figure 4.13c).

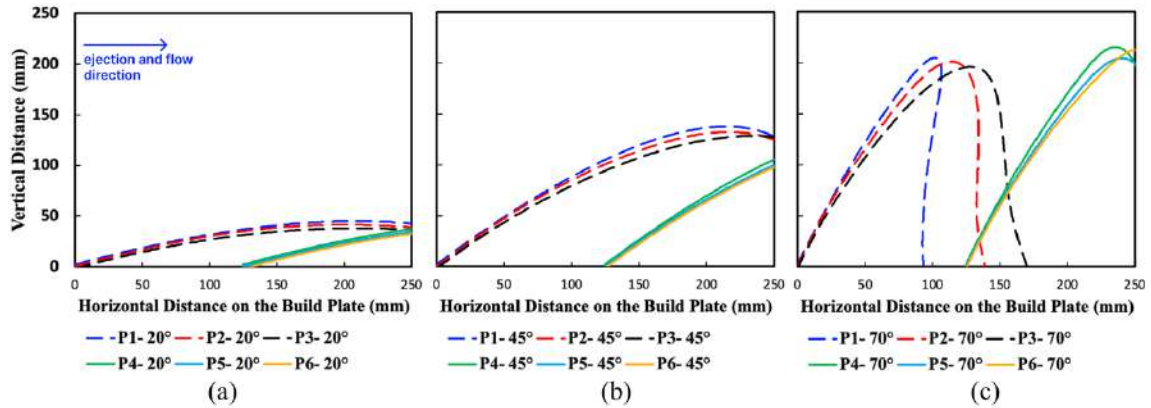


Figure 4.13: Trajectories of 120 μm Stainless steel 316L spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70°

ii. Spatter Particles Ejected in the Direction of Argon Gas Flow

At a 20° ejection angle, it was noted that all 120 μm spatters ejected from the middle of the build plate (P4, P5, and P6) against the gas flow direction, were transported beyond the build plate. However, among the spatters ejected at the edge of the build plate, only P7 was transported away from the build plate, facilitated by the inert gas flow (Figure 4.14a). As the inert gas flow acts in the opposite direction to the spatter generation, it prevented the particles from traveling beyond the build plate. Instead, it redirected them back towards the build plate. The gas flow had minimal influence on the spatter ejected at P7, since the gas flow velocity in this region was low in comparison to the other regions. Furthermore, all particles ejected at 45° were deposited outside the build plate (Figure 37b). At 70°, all spatters ejected from the middle of the build plate (P4, P5, and P6) were deposited outside the build plate, while those ejected at the edge of the build plate (P7, P8, and P9) were deposited on the build plate (Figure 4.14c).

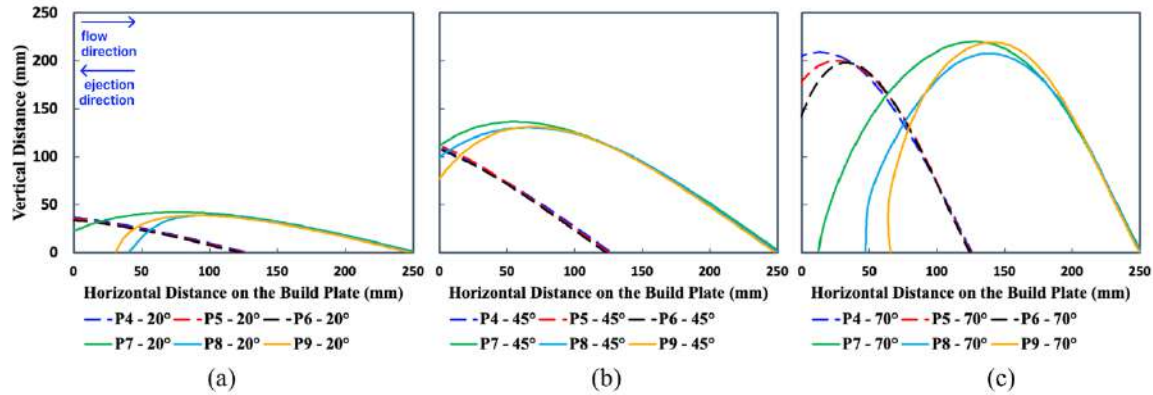


Figure 4.14: Trajectories of 120 μm Stainless steel 316L spatters ejected at various ejection angles in opposite direction to the flow (a) 20° (b) 45° (c) 70°

c) 180 μm Spatter Particles

Particle trajectories for spatter particles ejected in and against the direction of argon gas flow are shown in Figure 4.15a-c and Figure 4.15d-f respectively. Results for 180 μm SS316L spatter particles ejected in the direction of the gas flow show that all particles were deposited on the build plate for all ejection angles, as shown in Figure 4.15a-c. This is due to the density and speed of the spatters that hinder the particles from being transported outside the build plate. Similar to the trends observed previously, 180 μm spatter particles ejected at different locations against the flow direction were also deposited on the build plate (Figure 4.15d-f).

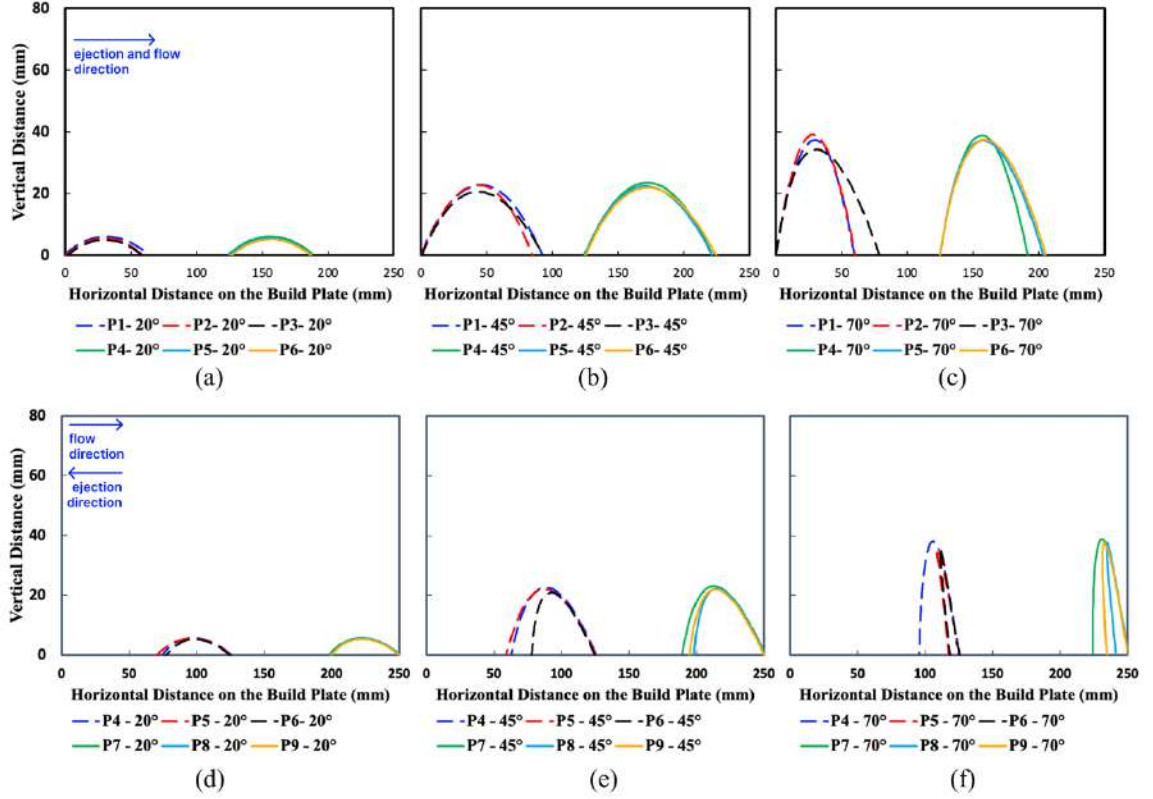


Figure 4.15: Trajectories of 180 μm Stainless steel 316L spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70° and in opposite direction to the flow (d) 20° (e) 45° (f) 70°

Figure 4.16 presents an overview of the landing sites on the build plate, encompassing various ejection angles, spatter sizes, and flow directions investigated in this study. The findings indicate that particles measuring 60 μm , when ejected both in the direction of flow and against it, were consistently deposited outside the build plate. This outcome can be attributed to their diminutive size and the accompanying high ejection velocities, which facilitated their escape from the region characterized by elevated gas flow velocities. Importantly, it was observed that the recirculation flow did not exert any discernible influence on the trajectory of these small particles.

Furthermore, all 120 μm spatters discharged from the middle of the build plate (specifically, P4, P5, and P6), regardless of whether they were directed with or against the flow, were consistently found to settle outside the build plate. This phenomenon was

attributed to the notable high flow velocities observed in these regions. Consequently, it is worth emphasizing the middle of the build plate as a safe zone in relation to the 120 μm spatters.

Lastly, all 180 μm spatters, irrespective of their point of ejection, were deposited on the build plate as the gas flow was unable to transport these particles away from the build area.

It is pertinent to note that an increased gas flow rate may indeed facilitate the transport of these particles; however, it might lead to the potential risk of particle blow-off from the powder-bed.

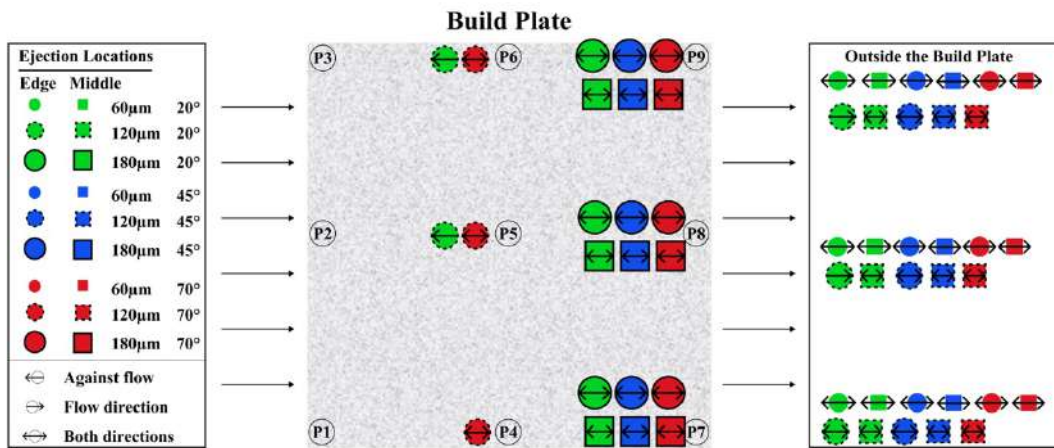


Figure 4.16: Schematic illustrating the landing locations (both on and off the build plate) of SS316L spatters. The circular shape is indicative of spatters ejected from the edges (P1, P2, P3, P7, P8, and P9), while the square shape denotes ejections originating from the middle of the build plate (P4, P5, and P6).

4.4.3 Hastelloy Spatters

a) 60 μm Spatter Particles

Spatter particles ejected in and against the direction of argon gas flow are shown in Figure 4.17a-c and Figure 4.17d-f respectively. It was observed that all 60 μm Hastelloy X spatters ejected from all ejection angles (20°, 45°, and 70°) in the flow direction were deposited outside the build plate (Figure 4.17a-c). This discernible pattern persisted for particles

ejected counter to the flow, irrespective of the angle of ejection (Figure 4.17d-f). These trends were observed due to the small size and high ejection speeds of these spatter particles.

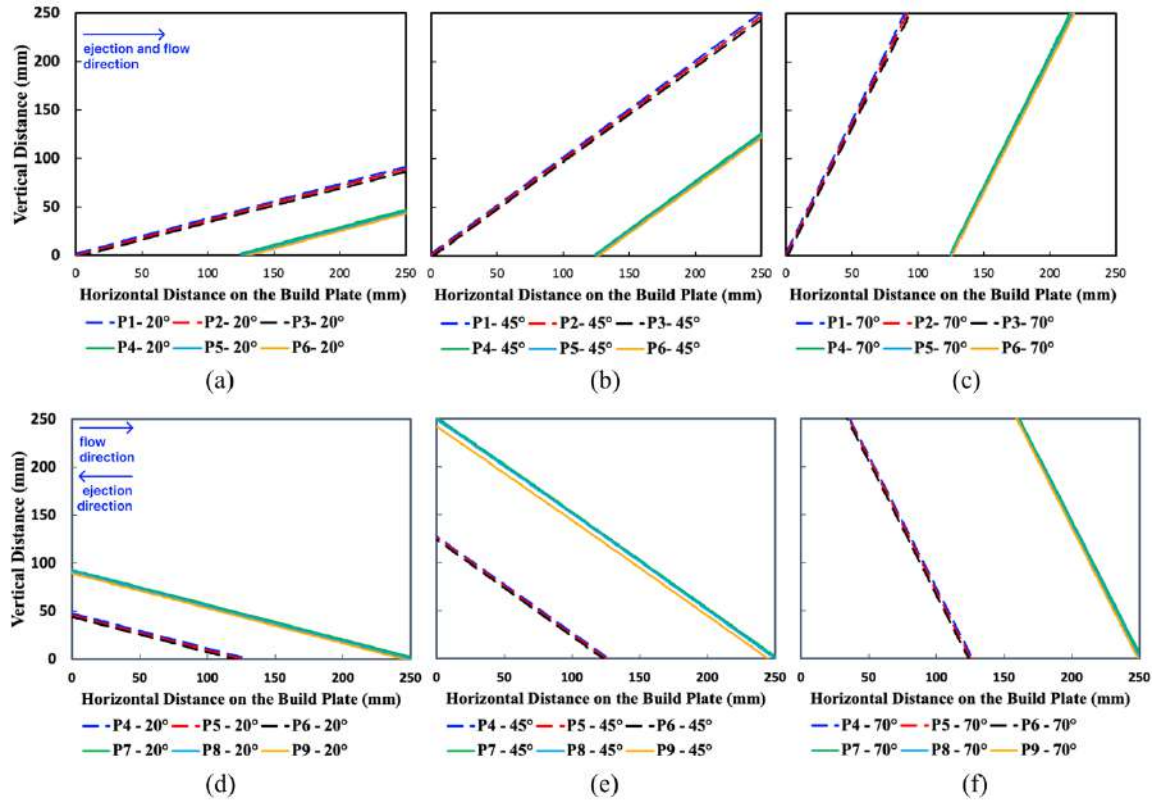


Figure 4.17: Trajectories of 60 μm Hastelloy X spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70° and in opposite direction to the flow (d) 20° (e) 45° (f) 70°

b) 120 μm Spatter Particles

i. Spatter Particles Ejected in the Direction of Argon Gas Flow

The 120 μm Hastelloy X particles ejected at 20° and 45° in the flow direction were transported beyond the build plate (Figure 4.18a-b). Nonetheless, a distinctive trend was noted for spatters ejected at 70°. Spatters expelled at 70° from the edge of the build plate (P1, P2, and P3) were deposited on the build plate. It was observed that, at this ejection angle, the spatters traveled a higher vertical distance in comparison to their horizontal

displacement. Conversely, spatters ejected from the middle of the build plate (specifically, P4, P5, and P6) were all deposited outside (Figure 4.18c).

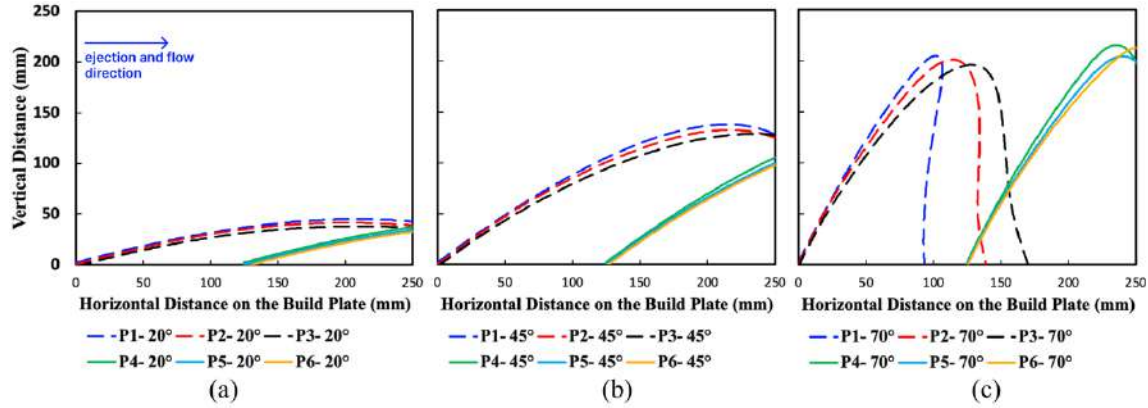


Figure 4.18: Trajectories of 120 μm Hastelloy X spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70°

ii. Spatter Particles Ejected in the Direction of Argon Gas Flow

In the case of 120 μm Hastelloy X spatter particles ejected at 20° angle against the gas flow, their transport beyond the build plate was contingent on their ejection point. Specifically, when ejected from the middle of the build plate (P4, P5, P6), they were consistently observed to settle outside the build plate. However, for those spatter particles ejected from the edge of the build plate (P7, P8, P9), it was notable that only P7 was deposited outside the build plate (Figure 4.19a) as observed for SS316L. This occurrence can be ascribed to the low gas velocity in this region, compared to the other regions. Consequently, this low gas velocity had negligible impact on redirecting the spatters in an opposing direction.

Likewise, spatter particles ejected at 45°, were consistently settled outside the build plate (Figure 4.19b). Furthermore, at an ejection angle of 70°, a consistent pattern emerged wherein all spatter particles ejected from the edge of the build plate were found to deposit

on the build plate. In contrast, spatter particles ejected from the middle of the build plate (P4, P5, P6) exhibited a consistent tendency to settle outside the build plate (Figure 4.19c).

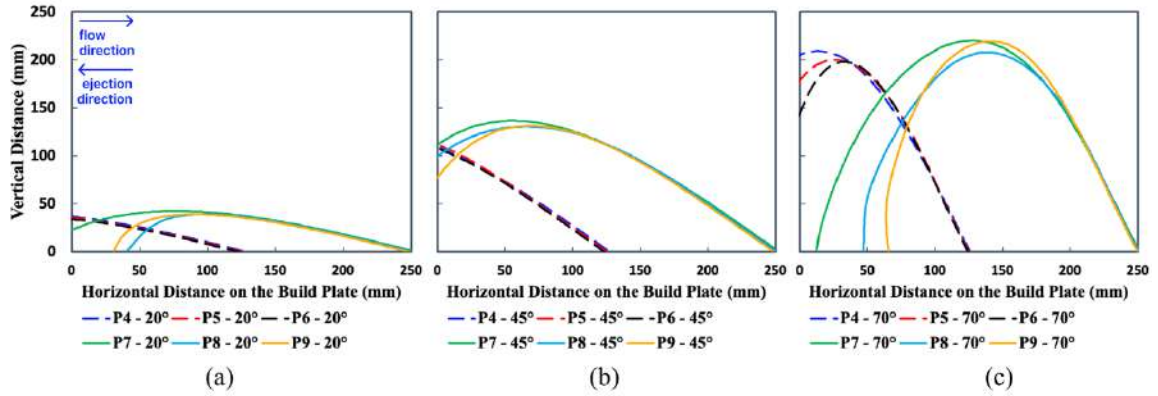


Figure 4.19: Trajectories of 120 μm Hastelloy X spatters ejected at various ejection angles in opposite direction to the flow (a) 20° (b) 45° (c) 70°

c) 180 μm Spatter Particles

Figure 4.20a-c and Figure 4.20d-f shows the trajectories of spatter particles discharged both in and against the argon gas flow, respectively. A notable observation indicates that spatter particles measuring 180 μm , when ejected in the direction of the gas flow, were consistently found to deposit onto the build plate for all ejection angles (Figure 4.20a-c). Similar behavior was observed for Hastelloy X 180 μm spatter particles ejected against the inert gas flow. Due to the particle size, spatters from all locations were deposited on the build plate (Figure 4.20d-f).

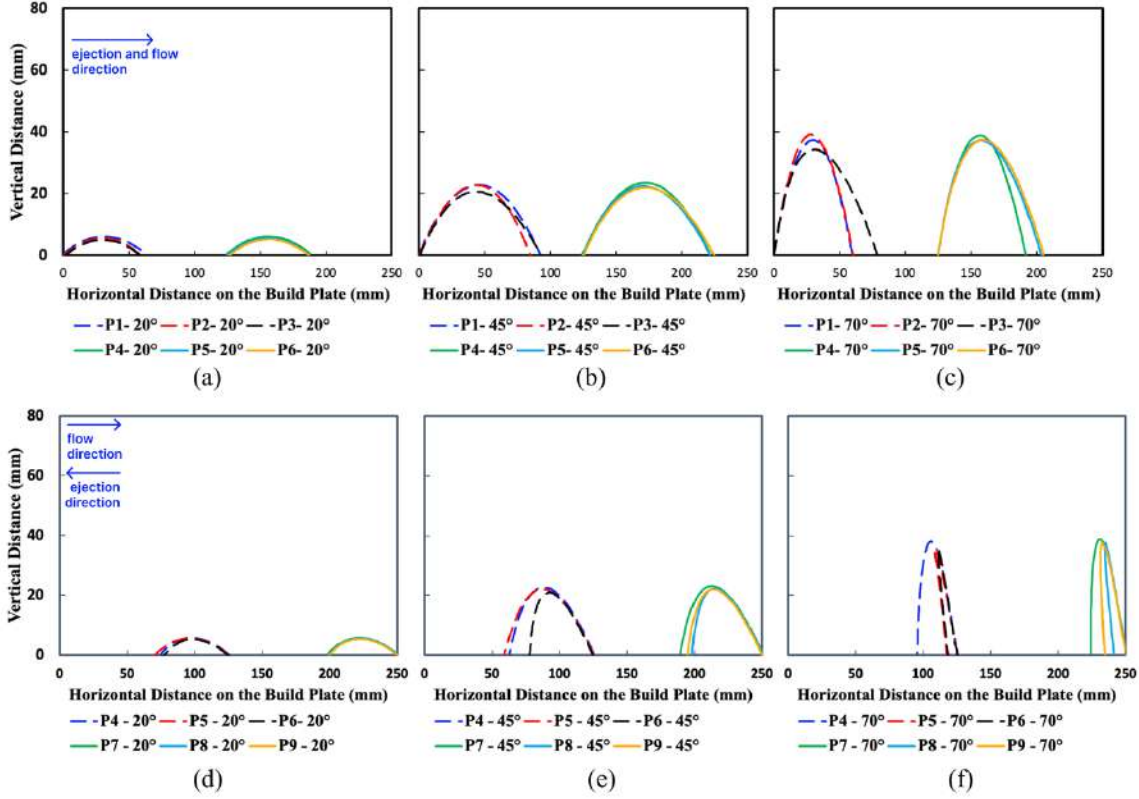


Figure 4.20: Trajectories of 180 μm Hastelloy X spatters ejected at various ejection angles in the same direction as the flow (a) 20° (b) 45° (c) 70° and in opposite direction to the flow (d) 20° (e) 45° (f) 70°

Figure 4.21 provides a comprehensive overview of the landing sites of Hastelloy X particles in relation to the build plate, accounting for various parameters including ejection angles, spatter sizes, and ejection directions. In summation, it is evident (Figure 4.21) that 60 μm particles, irrespective of the ejection direction (both in and against the flow direction), were consistently deposited outside the build plate. This phenomenon can be attributed to their small size and the accompanying high ejection velocities. Similar to observations made with SS316L, all 120 μm spatter particles, when ejected from the middle of the build plate (P4, P5, and P6), whether in the direction of the flow or counter to it, were deposited outside the build plate. This underscores the efficacy of positioning the printing operation in this particular locale to ensure optimal spatter removal.

Furthermore, as observed for all materials investigated, 180 μm spatter particles regardless of flow direction, ejection angle, or ejection point, were consistently deposited on the build plate. The large size, deterred their expulsion beyond the boundaries of the build plate. It is pertinent to note that owing to the similar densities between SS316L and Hastelloy X powders, their respective spatters exhibited similar trajectories in most instances.

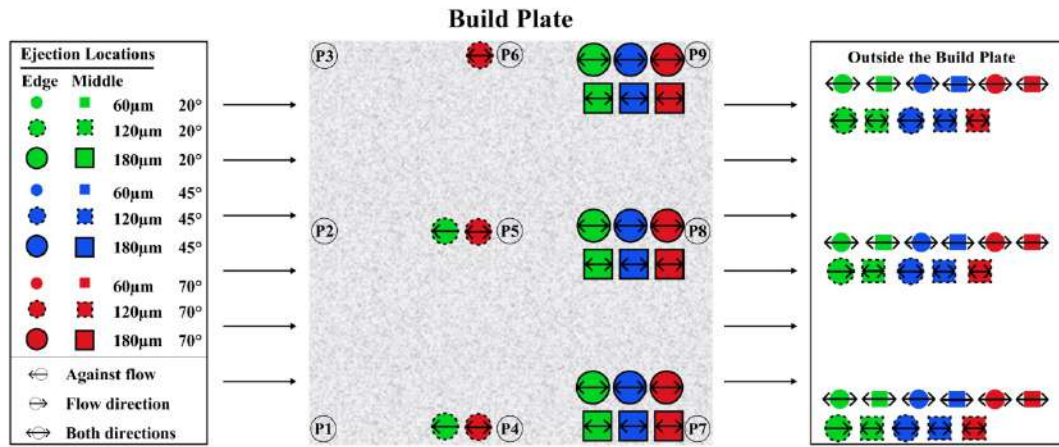
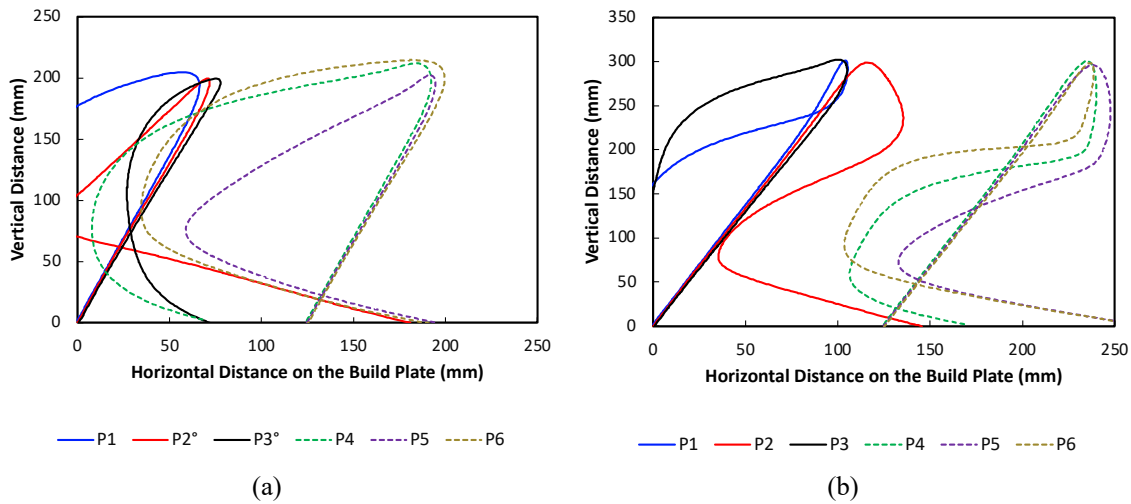


Figure 4.21: Schematic illustrating the landing locations (both on and off the build plate) of Hastelloy X spatters. The circular shape is indicative of spatters ejected from the edges (P1, P2, P3, P7, P8, and P9), while the square shape denotes ejections originating from the middle of the build plate (P4, P5, and P6).

4.5 Effect of Recirculation Zone on Spatter Trajectories

In the previous section, the gas velocity in the recirculation zone has been identified as one of the reasons of spatter deposited on the build plate. This effect is more pronounced for light materials ejected at high ejection angle. Although the gas velocity in this zone (approximately 0.7m/s) is less than the inlet velocity (Figure 4.4), it still has a significant impact on materials with low density. This section investigates the critical material density beyond which the gas flow in the recirculation zone does not have any influence. Figure 4.22 shows the 60 μm spatter sizes of different densities (2700 kg/m³, 4000 kg/m³, 5000 kg/m³, and 6000 kg/m³) ejected at 70° ejection angle with ejection velocity kept constant.

Particles of size 60 μm size were chosen since the velocity in the recirculation zone has a higher effect on smaller particles. The results show that although the spatters travelled longer vertical distance with an increase in density, the velocity in the recirculation zone still had an effect on redirecting the spatters. Figure 4.22 shows an insignificant effect of recirculation zone for densities of 6000 kg/m^3 . Therefore, it can be inferred that materials like AlSi10Mg (2700 kg/m^3), Ti-6Al-4V (4420 kg/m^3), Magnesium alloy WE43 (1800 kg/m^3), will most likely be redirected in the recirculation zone, while Inconel 718 (8200 kg/m^3), SS316L (7950 kg/m^3), Hastelloy X (8220 kg/m^3), CoCrMo (8400 kg/m^3) won't be affected by the gas flow in the recirculation zone. This means that small sized spatters of materials with density lower than 6000 kg/m^3 , ejected at higher ejection angles and ejection velocity were more susceptible to being deposited on the build plate, while small sized spatters of materials with higher density 6000 kg/m^3 might be transported away from the build plate due to the recirculation zone.



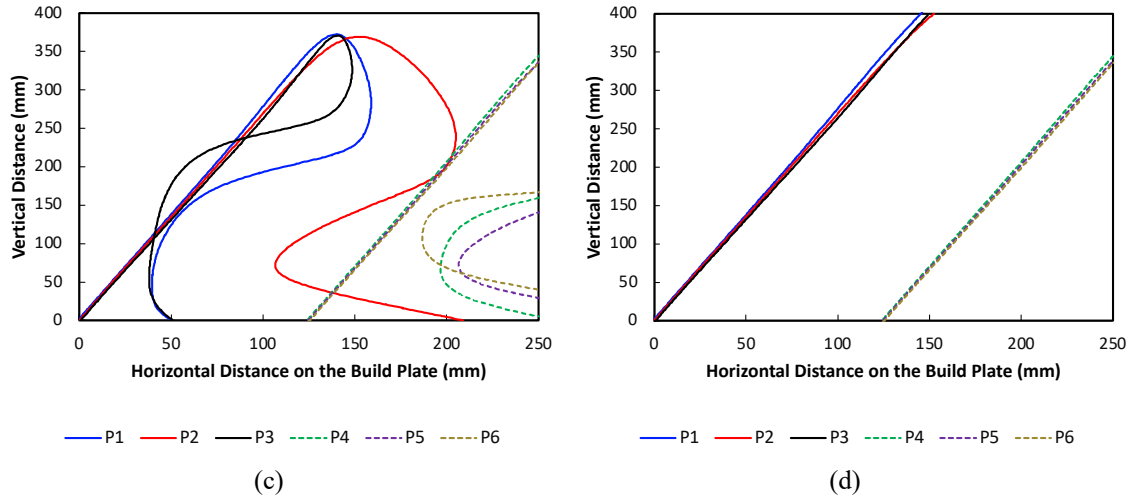
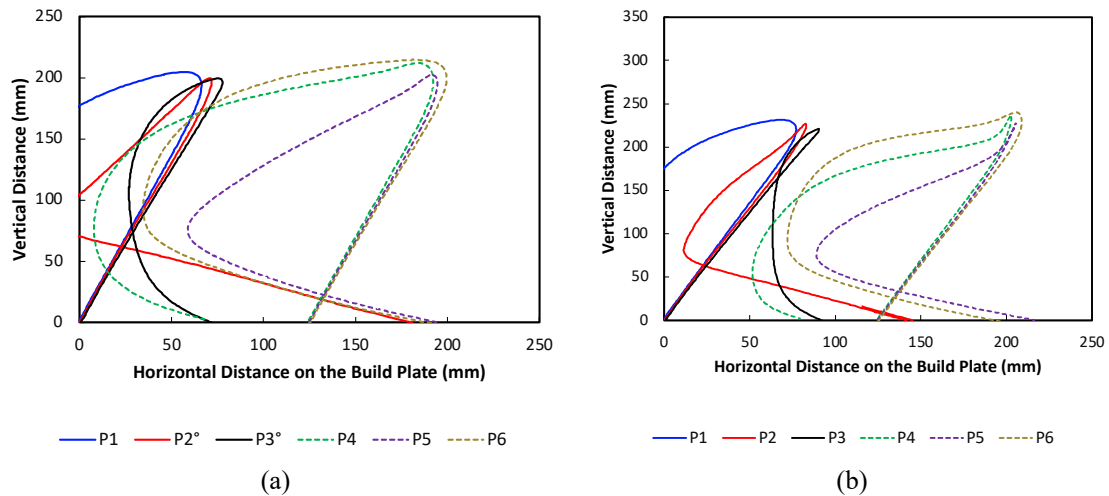


Figure 4.22: The influence of the recirculation zone on the trajectories of spatter materials with different densities ejected with constant ejection velocity (a) AlSi10Mg 2700 kg/m³ (b) 4000 kg/m³ (c) 5000 kg/m³ (d) 6000 kg/m³

Similarly, the 60 μm spatter sizes of different densities (2700 kg/m³, 4000 kg/m³, 6000 kg/m³, and 8000 kg/m³) were also ejected with constant momentum at 70° ejection angle. It was observed that the effect of the recirculation zone on spatters with 8000 kg/m³ density wasn't as pronounced as spatters with low density (for example AlSi10Mg with 2700 kg/m³). The results show that all spatters were redirected back to the build plate as seen in Figure 4.23. This shows that regardless of the density of the material, spatters ejected at high ejection angle will likely be redirected back to the build plate when they approach the recirculation zone as their velocity decreases.



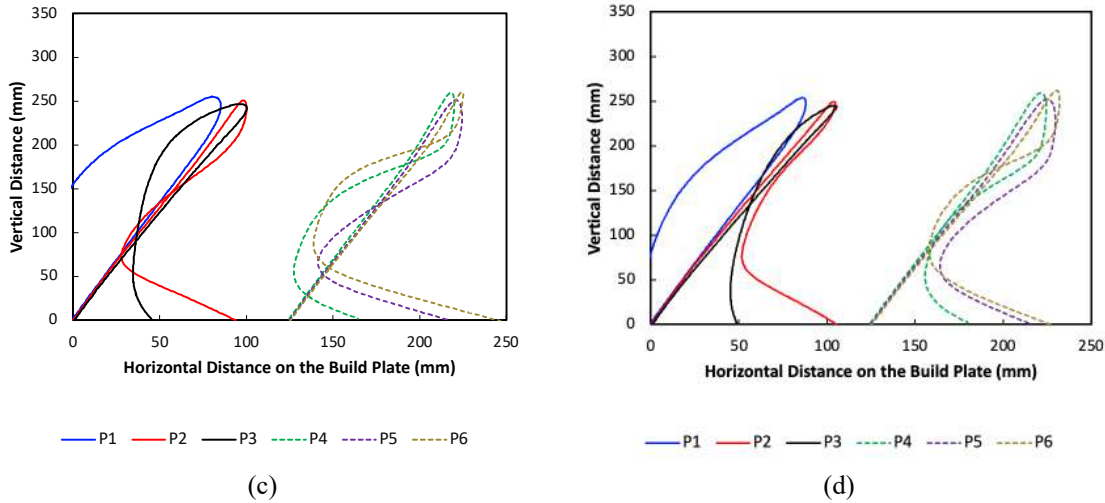


Figure 4.23: The influence of the recirculation zone on the trajectories of spatter materials with different densities ejected with constant momentum (a) AlSi10Mg 2700 kg/m³ (b) 4000 kg/m³ (c) 6000 kg/m³ (d) 8000 kg/m³

4.6 Effect of Gas Flow Rate on Spatter Trajectories

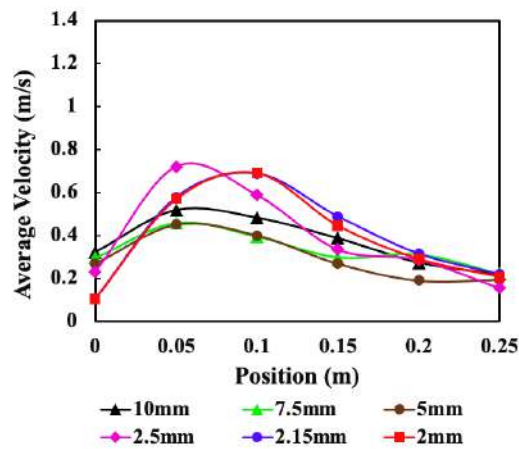
In the previous section, the trajectories of spatters from three different materials (AlSi10Mg, SS 316L, and Hastelloy X) were examined using the Renishaw AM 250 LPBF machine at a baseline flow rate of 250 LPM. Having observed the impact of the 250 LPM gas flow rate on spatter transport, this section investigates four different gas flow rates (250 LPM, 500 LPM, 750 LPM, and 1000 LPM) to understand the effect of flow rate on spatter transport. While it's established that increasing the flow rate leads to a higher number of spatters being transported away from the build plate (Section 2.5.1), it's crucial to assess the effect of flow rate on each material and spatter size. This helps determine the optimal flow rate for each material and spatter size.

It's important to note that this section only considers two materials (AlSi10Mg and SS316L) as there was no significant difference in the spatter trajectories between SS316L and Hastelloy X (Section 4.4). This similarity can be attributed to the similar densities between the two materials (SS316L—7950 kg/m³ and Hastelloy X—8220 kg/m³). While higher gas flow rates may demonstrate better spatter clearance, increasing the gas flow

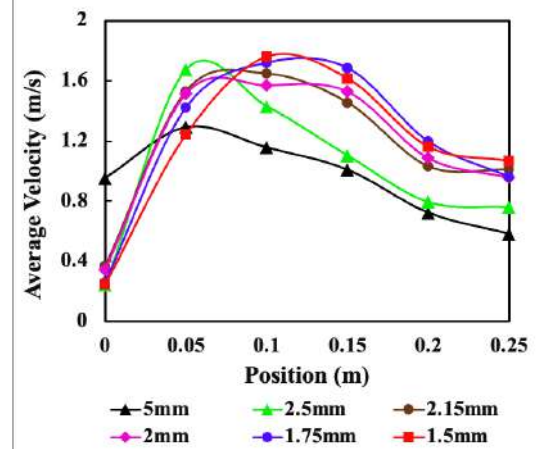
rates increases the risk of powders being blown away from the build plate. This effect wasn't considered in this study.

4.6.1 Grid Independence Test

Grid independence test was also carried out to determine the optimal mesh to be used for each flow rate. This was done to select the optimal mesh size beyond which there no significant difference in the solution was observed. Similar to what was discussed in Section 4.1, the average velocity over the entire build plate was used as the mesh independence criteria. Figure 4.24 shows the average velocity profiles over the build plate at several locations for each gas flow rate. A, 2.15 mm mesh size (Section 4.1) was found to be the optimal mesh size for 250 LPM gas flow rate as shown in Figure 4.24a. Figure 4.24b shows the velocity distribution along the build plate with a gas flow rate of 500 LPM. It was observed that the results produced by the 1.75 mm were close to those produced using 1.5 mm mesh. Hence, 1.75 mm mesh size was used with flow rates of 500 LPM. Similarly, 1.5 mm and 1.25 mm mesh sizes were found to be the optimal mesh sizes for the 750 LPM and 1000 LPM gas flow rates respectively (Figure 4.24c & d).



(a)



(b)

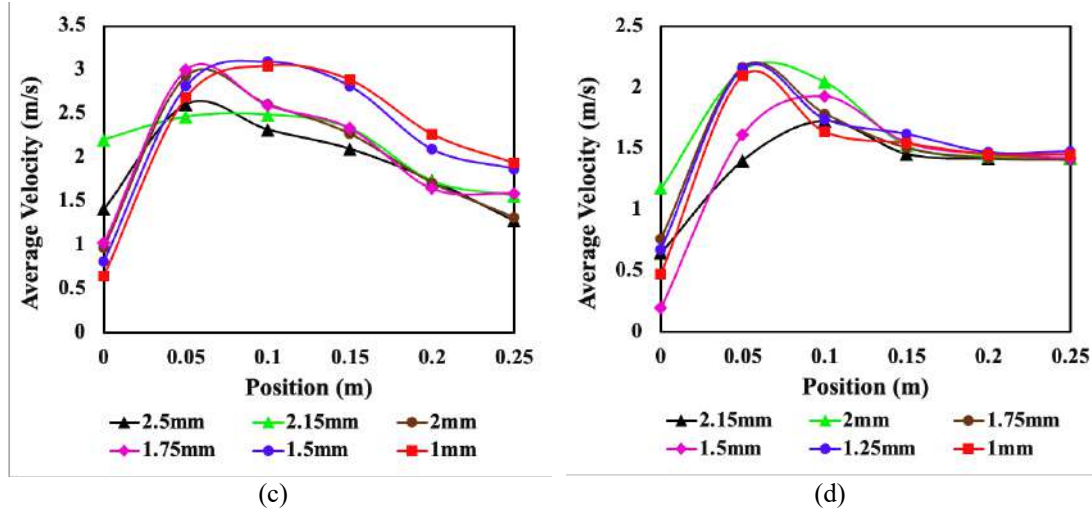


Figure 4.24: Average gas flow velocity along the left edge of the build plate using various mesh sizes (a) 250LPM (b) 500LPM (c) 750LPM (d) 1000LPM

4.6.2 Spatter Clearance Rate

In this section, the spatter removal percentage was determined for each material (AlSi10Mg and SS 316L) subjected to different flow rates (250 LPM, 500 LPM, 750 LPM, and 1000 LPM). This was done to determine the optimal flow rate for each spatter size and material. The spatter clear rate is given as ratio of number of particles that fall outside the build plate to the total number of particles.

a) AlSi10Mg Spatter Clearance Rate

Table 4.2 presents an overview of AlSi10Mg particles ejected with a gas flow rate of 250 LPM. Particles were ejected in and against flow (Figure 3.2). It was observed that a significant number of the 60 μm size particles were deposited outside the build plate with a clear rate of 50% compared to the 120 μm and 180 μm size particles with a clear rate of 36.11% and 8.33%, respectively. This can be attributed to the light weight of the particles which are easily transported by the inert gas. A total of 31% clear rate was recorded for all AlSi10Mg particles ejected at 250 LPM.

Table 4.2: Summary of AlSi10Mg particles ejected at 250 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	18	36	50.00%
120	13	36	36.11%
180	3	36	8.33%
Total	34	108	31%

Similarly, increasing the gas flow rate to 500 LPM had a significant effect on the clear rate of the AlSi10Mg particles. About 67% of the 60 μm size particles were deposited outside the build plate compared to 50% observed with 250 LPM gas flow rate. Similarly, the 120 μm and 180 μm size particles also experienced an increase in the spatter clear rate, with the 120 μm particles having an improved clear rate of 72% compared to 36% with 250 LPM. The 180 μm particles also had an improved clear rate of 22% as seen in Table 4.3. In general, the AlSi10Mg particles ejected at 500 LPM saw an overall increase in spatter clear rate from 31% (at 250 LPM) to 54%. The increase in the gas velocity was able to blow more spatters away from the build plate, especially the bigger spatters, hence an increase in the spatter clear rate.

Table 4.3: Summary of AlSi10Mg particles ejected at 500 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	24	36	66.67%
120	26	36	72.22%
180	8	36	22.22%
Total	58	108	54%

Furthermore, similar to the effects observed at 500 LPM, increasing the gas flow rate to 750 LPM resulted in an increase in the number of spatters deposited outside the build plate. This coincided with an increase for all AlSi10Mg ejected particles, increasing from 54% at 500 LPM to 65%. The increase in gas velocity facilitated the removal of larger spatters from the build plate. This effect was notably observed for 180 μm particles, where the spatter clearance rate increased from 22% to approximately 42% (Table 4.4) as the gas flow rate was increased from 500 LPM to 750 LPM.

Table 4.4: Summary of AlSi10Mg particles ejected at 750 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	31	36	86.11%
120	24	36	66.67%
180	15	36	41.67%
Total	70	108	65%

Finally, using 1000 LPM gas flow rate also resulted in a notable increase in the overall clearance rate of all ejected AlSi10Mg particles. Notably, this gas flow rate yielded the highest total clearance rate among all rates considered in this study, boasting a clear rate of 70% (Table 4.5). Interestingly, this rate marked a clear increase of over 100% in comparison to the baseline design utilizing 250 LPM. It is worth noting, however, that while this flow rate demonstrated superior spatter clearance, there exists an upper threshold for gas flow rate within the build chamber, as further increases may elevate the risk of powder dispersion from the build plate.

Table 4.5: Summary of AlSi10Mg particles ejected at 1000 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	29	36	80.56%
120	30	36	83.33%
180	17	36	47.22%
Total	76	108	70%

Figure 4.25a - d show the clearance rate of all AlSi10Mg particles ejected at each flow rate. It was observed that 750 LPM gas flow rate (Figure 4.25c) was the most effective flow rate for 60 μm spatters, with a clearance rate 86%. 1000 LPM gas flow rate (Figure 4.25d) was found to be best flow rate for effective spatter removal for 120 μm and 180 μm spatters, boasting a clear rate of 83% and 47% respectively. Figure 4.25e presents an overview of the overall AlSi10Mg clearance rates for various gas flow rates examined in this study. The 1000 LPM gas flow rate demonstrated the highest clearance rate at 70%, whereas the 250 LPM gas flow rate yielded the lowest clearance rate at 31%.

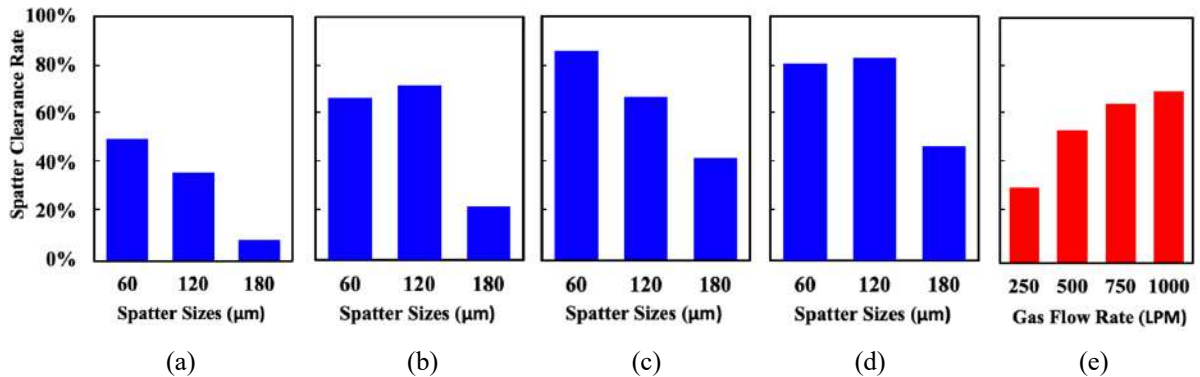


Figure 4.25: Summary of AlSi10Mg spatter clearance rates of all sizes and gas flow rates used in this study (a) 250LPM (b) 500LPM (c) 750LPM (d) 1000LPM (e) Overall AlSi10Mg clearance rate of all gas flow rates used in this study

b) SS316L Spatter Clearance Rate

Table 4.6 shows the summary of SS316L particles ejected at a gas flow rate of 250 LPM. Notably, all 60 μm particles were deposited outside the build plate, yielding a 100% clearance rate. Moreover, a clearance rate of 78% was recorded for the 120 μm particles, while none of the 180 μm particles were deposited outside the build plate. This observation shows that 250 LPM was not sufficient to transport larger particles, resulting in a 0% clearance rate for 180 μm particles. In total, a 59% clearance rate was observed for all ejected AlSi10Mg particles at 250 LPM.

Table 4.6: Summary of SS316L particles ejected at 250 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	36	36	100.00%
120	28	36	77.78%
180	0	36	0.00%
Total	64	108	59%

Much like the observations at 250 LPM, increasing the gas flow rate to 500 LPM resulted in the transport of all 60 μm particles beyond the build plate. Furthermore, there was a reduction in the number of 120 μm particles found outside the build plate when the gas flow rate was increased to 500 LPM, with the clearance rate decreasing from 78% to 64%. Additionally, the increased gas flow rate transported all 180 μm particles ejected at 45° and 70° ejection angle from the edge of the build plate (P7, P8, and P9) against the flow direction beyond the build plate, thereby increasing the clearance rate from 0 to about 6% (Table 4.7). A slight decline in the overall clearance rate was observed with the 500 LPM

gas flow rate (from 59% to 56%). This can be attributed to the redirection of the 120 μm particles ejected against the flow direction as they approached the strong gas velocity region near the inlet. This led to the reduction in clearance rate of the 120 μm size particles dropping from 77.78% observed in 250 LPM to 63.89%, thereby slightly reducing the overall clearance rate.

Table 4.7: Summary of SS316L particles ejected at 500 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	36	36	100.00%
120	23	36	63.89%
180	2	36	5.56%
Total	61	108	56%

In line with observations at 500 LPM, increasing the gas flow to 750 LPM led to an increase in clearance rate. This correlated with an increase in the overall clearance rate for all ejected SS316L particles, increasing from 56% observed at 500 LPM to 63% (Table 4.8). Notably, the clearance rates for 60 μm and 120 μm particles remained consistent between the two flow rates. However, a discernible difference was observed with 180 μm particles, where the clearance rate increased from 6% to 25% at 750 LPM. This highlights that increasing the gas flow tends to transport larger spatters away from the build plate.

Table 4.8: Summary of SS316L particles ejected at 750 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	36	36	100%
120	23	36	63.89%
180	9	36	25.00%
Total	68	108	63%

In conclusion, employing a gas flow rate of 1000 LPM yielded the highest overall clearance rate among all ejected SS316L particles, achieving a clearance rate of 72% (Table 4.9). Nonetheless, it's important to highlight that, despite its superior spatter clearance, there is a limit to the permissible gas flow rate within the build chamber. Exceeding this limit could potentially increase the risk of powder dispersion from the build plate.

Table 4.9: Summary of SS316L particles ejected at 1000 LPM

Particle Size (μm)	Particles deposited outside build plate	Particles ejected	Removal percentage
60	36	36	100.00%
120	27	36	75.00%
180	15	36	41.67%
Total	78	108	72%

Figure 4.26a – d show the clearance rate of all SS316L particles ejected at each flow rate. It was observed that all 60 μm particles ejected were deposited outside the build plate, boasting a clearance rate of 100% for all gas flow rates considered in this study. 250 LPM gas flow rate was the most effective flow rate for 120 μm spatters (Figure 4.26a), with a clearance rate 78% while the 1000 LPM gas flow rate was found to be best flow rate for

effective spatter removal for 180 μm spatters (Figure 4.26d), boasting a clear rate of 42%. Figure 4.26e shows the summary of the overall SS316l overall clearance rate of all gas flow rate used in this study, with 1000 LPM gas flow rate producing the best overall clearance rate of 72%, while the 500 LPM gas flow rate gave the lowest clearance rate of 56%.

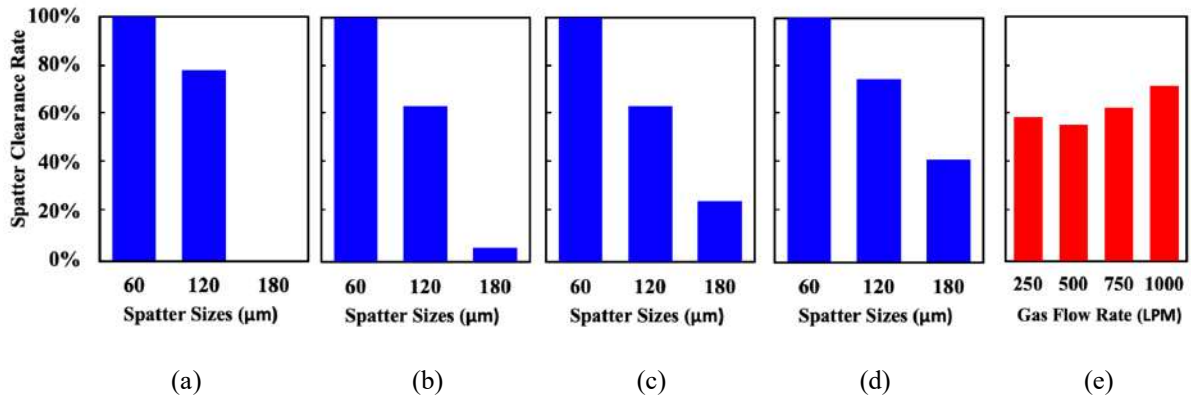


Figure 4.26: Summary of SS316L spatter clearance rates of all sizes and gas flow rates used in this study (a) 250LPM (b) 500LPM (c) 750LPM (d) 1000LPM (e) Overall SS316L clearance rate of all gas flow rates used in this study

4.7 Spatter Behaviors

Ejection trajectories of spatter particles highlighted the various ways in which spatters behave once ejected from the LPBF build plate. This behavior is dependent on the material, size, ejection angle, and location. The analysis in this work highlights three dominant mechanisms that lead to deposition of spatter particles. Spatter particles either deposit directly onto the build plate, or are conveyed by the airflow, or are redirected within the recirculation zone. Large spatters get deposited directly on the build plate whereas small spatters that leave the build plate can be redeposited on the build plate if redirected by the inert gas flow. This redirection is particularly noticeable for low-density materials of all sizes, especially for smaller particles.

Consequently, small-sized spatters or those of low-density materials ejected in the direction opposite to the flow can be deposited on the build plate if they are influenced by the flow. Furthermore, small-sized spatters of low-density materials ejected in the direction of flow may be redirected back to the build plate if they enter the recirculation zone. At higher ejection angles, the lower recirculation velocities are sufficient to deposit the spatter particles on the build plate. Figure 4.27 provides instances of the various manners in which spatters are deposited, both with and against the inert gas flow. The mechanisms causing spatter particles to leave the build chamber align with those discussed earlier.

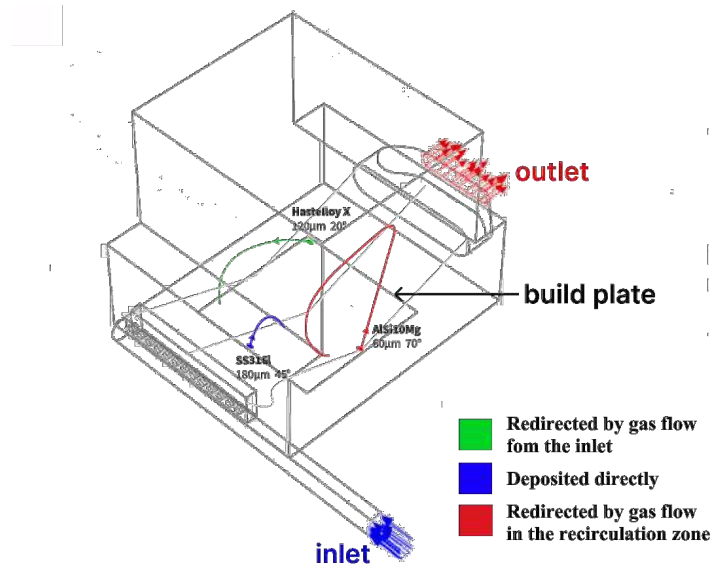


Figure 4.27: Various mechanisms for the deposition of spatters onto the build plate

CHAPTER 5

CONCLUSIONS

The influence of spatter particles on the quality and performance of laser powder-bed fusion (LPBF) parts is a well-established concern. This study focused on investigating the spatter behavior and transport within a Renishaw AM250 LPBF machine, considering various materials (AlSi10Mg, SS316L, and Hastelloy X). This work delved into the effects of spatter particle size, ejection angle, inert gas flow rate, and ejection locations on spatters ejected both along and against the direction of inert gas flow. Validated numerical simulations were performed using Ansys Fluent Computational Fluid Dynamics (CFD) package, with Discrete Phase Model (DPM) to simulate the interactions between the inert gas flow and spatter particles within the build chamber. The key findings from the study are outlined as follows:

- The gas flow within the build chamber exhibited non-uniformity along the length and height of the LPBF build chamber.
- The configuration of the gas flow system and chamber generated notable recirculation zones, leading to the redeposition of small-sized spatter particles at higher ejection angles with densities below 6000 kg/m^3 .
- All $60 \text{ }\mu\text{m}$ spatter particles of AlSi10Mg, SS316L, and Hastelloy X ejected at a 20° angle in the flow direction were transported outside the build plate. However, at higher ejection angles, particularly at 70° , the gas flow in the recirculation zone

affected AlSi10Mg spatter particles, causing them to be redirected back to the build plate.

- A notably greater proportion of 60 μm AlSi10Mg spatters, ejected in the opposite direction to the flow, were redirected to the build plate, influenced by high velocities in the regions close the inlet.. Conversely, all 60 μm SS316L and Hastelloy X spatters, ejected in the opposite direction to the flow, were transported beyond the build plate.
- The predominant outcome for the majority of 120 μm spatters, irrespective of material (AlSi10Mg, SS316L, and Hastelloy X), ejected in the flow direction from the middle of the build plate (P4, P5, and P6), was their deposition outside the build plate.
- Likewise, all 120 μm SS316L and Hastelloy X spatters ejected in the direction opposite to the gas flow from the middle of the build plate (P4, P5, and P6) were transported beyond the build plate. However, a notable distinction was observed for the 120 μm AlSi10Mg spatters ejected from the middle of the build plate, as the majority of them were redirected towards the build plate. This redirection was attributed to their low density
- Irrespective of the ejection location and gas flow direction, all 180 μm AlSi10Mg, SS316L, and Hastelloy X spatters landed on the build plate due to their larger size and weight. The only exceptions were observed with AlSi10Mg spatters ejected at 70° from the edge of the build plate (P7, P8, and P9), which landed outside the build plate.

- The optimal gas flow rate for efficient removal of 60 μm AlSi10Mg spatters was found to be 750 LPM, achieving a clearance rate of 86%. For 120 μm and 180 μm spatters, the most effective gas flow rate was 1000 LPM, resulting in clearance rates of 83% and 47% respectively.
- All 60 μm SS316L particles were consistently deposited outside the build plate, regardless of the flow rate, achieving a clearance rate of 100%. For 120 μm spatters, a gas flow rate of 250 LPM proved to be the most effective, resulting in a clearance rate of 78%. On the other hand, for 180 μm spatters, a gas flow rate of 1000 LPM was found to be the most efficient, yielding a clearance rate of 42%.
- The overall clearance rate for AlSi10Mg and SS316L spatters was highest at 1000 LPM (70% and 72%, respectively) while, the lowest clearance rate was at 250 LPM (31%) and 500 LPM (56%), respectively.
- The analysis of spatter trajectories unveiled three fundamental mechanisms leading to spatter particles landing on the build plate: direct deposition, conveyance by airflow, or redirection within the recirculation zone.

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