Large scale selective laser melting : study of the effects and removal of spatter by the inert gas flow

Ahmad Anwar

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**LARGE SCALE SELECTIVE LASER MELTING:
STUDY OF THE EFFECTS AND REMOVAL OF
SPATTER BY THE INERT GAS FLOW**

**AHMAD BIN ANWAR
SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

2019

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STUDY OF THE EFFECTS AND REMOVAL OF
SPATTER BY THE INERT GAS FLOW**

AHMAD BIN ANWAR

School of Mechanical and Aerospace Engineering

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Abstract

In commercial Selective Laser Melting (SLM) machines, the removal of spatter particles and other undesired by-products is performed by pumping inert gas unidirectionally over the powder bed. However, traces of deposited spatter which are darker in contrast as compared to the fresh powder are often observed during the SLM process. The effectiveness of the inert gas flow in transporting spatter particles was identified as a critical hindrance in the expansion of the powder bed area. With respect to the SLM machines produced by SLM Solutions Group AG (Lübeck, Germany), the powder bed width for all the current machine variants is limited to 280 mm along the x axis. In this thesis, studies on the effects of spatter particles, their distribution on the powder bed and the effectiveness of the inert gas flow, which were done experimentally and with the use of simulations, are presented. Firstly, Analysis of Variance (ANOVA) was applied to statistically reveal that parts of higher Ultimate Tensile Strength (UTS) was significantly obtained when laser scanning against the gas flow, at higher gas flow velocity and when scanning close to the outlet. Video evidence provided by a high-speed camera successfully captured more sparks when scanning in the direction of the gas flow. The sparks were attributed to the burning of spatter particles which were blown into the path of the laser beam by the gas flow. Following this, the spatter mass and size distributions on the powder bed, downstream of the laser-scanned sites were experimentally evaluated to establish the ground truth. Insights into the computations of the Stokes number (Stk) revealed an exponential decay with respect to the distance travelled by the spatter particles suspended in the gas flow. For the first time, the investigations elucidated the limitations in the effectiveness of the inert gas flow in removing spatter beyond the 280 mm limit. Finally, simulations of spatter particles under the influence of the inert gas flow were conducted using Computational Fluid Dynamics (CFD) and the Discrete Phase Model (DPM) for particle tracking. The effects of vapour driven entrainment on spatter ejections were considered. Despite not accounting for the full complexities of the multi-physics phenomena during SLM, good agreement was achieved with the earlier established experimental data on the mass and size distributions.

*"Yesterday I was clever, so I wanted to change the world. Today I am wise,
so I am changing myself."*

- Jalal ad-Din Muhammad Rumi (also known as Rumi)

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

28 March 2019

Date

Ahmad Bin Anwar

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

28 March 2019

Date

Associate Professor Pham Quang Cuong

Authorship Attribution Statement

This thesis contains material from 3 paper(s) published in the following peer-reviewed journals/ from papers accepted at conferences in which I am listed as an author.

Part of chapter 2 has been published as **Anwar, A. B.**, & Pham, Q.-C. (2018a). Spattering phenomenon in selective laser melting: A review of spatter formation, effects and countermeasures. *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018)*, 3, 541-546.

The contributions of the co-authors are as follows:

- I proposed the direction for the review paper.
- I prepared the manuscript draft.
- The revision to the manuscript was undertaken together by me and Prof. Pham.

Chapter 3 has been published as **Anwar, A. B.**, & Pham, Q.-C. (2017). Selective laser melting of AlSi10Mg: Effects of scan direction, part placement and inert gas flow velocity on tensile strength. *Journal of Materials Processing Technology*, 240, 388-396.

The contributions of the co-authors are as follows:

- The initial project direction was proposed by Prof. Pham and I.
- I prepared the manuscript draft.
- I performed all the laboratory work at the School of Mechanical and Aerospace Engineering, NTU. I also analysed the data.
- The revision to the manuscript was undertaken together by Prof. Pham and I.

Chapter 4 has been published as **Anwar, A. B.**, & Pham, Q.-C. (2018b). Study of the spatter distribution on the powder bed during selective laser melting. *Additive Manufacturing*, 22, 86-97.

The contributions of the co-authors are as follows:

- The initial project direction was proposed by Prof. Pham and I.
- I prepared the manuscript draft.

- I performed all the laboratory work at the School of Mechanical and Aerospace Engineering, NTU. I also analysed the data.
- The revision to the manuscript was undertaken together by Prof. Pham and I.

28 March 2019

Date

Ahmad Bin Anwar

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Contents

Statement of Originality	i
Supervisor Declaration Statement	iii
Authorship Attribution Statement	v
Acknowledgements	ix
List of Tables	xiv
List of Figures	xvii
List of Publications	xviii
1 Introduction	1
1.1 Motivation	1
1.2 Objectives & Scope	2
1.3 Contributions	2
1.3.1 Effects of laser-spatter interactions in SLM	3
1.3.2 Spatter distribution on the powder bed	3
1.3.3 Effectiveness of inert gas flow in spatter removal	4
1.4 Thesis Outline	4
2 Literature Review	6
2.1 Additive Manufacturing	6
2.1.1 Metal-Based Additive Manufacturing	8
2.1.2 Large Scale AM	12
2.1.3 SLM of AlSi10Mg	13
2.2 Spatter in SLM	15
2.2.1 Formation and Characteristics of Spattering Phenomenon	16
2.2.2 Effects of Spattering	19

2.2.3	Countermeasures	19
2.2.4	Monitoring Systems	21
2.2.5	Role of Inert Gas in Build Chamber	22
2.3	Particle-laden Flow	23
2.4	Summary	26
3	Effects of laser-spatter-gas interactions on UTS of printed parts	27
3.1	Introduction	27
3.2	Materials & Method	28
3.2.1	SLM Parameters	28
3.2.2	Protocol	28
3.2.3	Analysis of the printed parts	30
3.2.4	Spatter	31
3.2.5	High-speed camera observation	31
3.2.6	Statistical analysis	32
3.3	Results	33
3.3.1	Tensile strength	33
3.3.2	Composition of spatter	34
3.3.3	Quantity of spatter collected near the outlet	36
3.3.4	Visual observation of laser-spatter-gas interactions	37
3.4	Discussion	38
3.4.1	Effect of gas flow velocity on part quality	38
3.4.2	Effect of scan direction on part quality	40
3.4.3	Spatter Accumulation	41
3.4.4	Other parameters that can influence part quality	42
3.5	Conclusion	43
4	Spatter distribution on the powder bed	44
4.1	Introduction	44
4.2	Materials and Methods	45
4.2.1	SLM Parameters	46
4.2.2	Gas Flow	47
4.2.3	Experiment protocol	47
4.3	Results	51
4.3.1	Image processing	51
4.3.2	Distribution of spatter mass on powder bed	55
4.3.3	Distribution of spatter particle size on powder bed	56
4.3.4	Correlation between spatter mass and percentage of spatter pixels (SP)	57
4.3.5	Statistical tests	57

4.4	Discussion	58
4.4.1	Effectiveness of image processing	58
4.4.2	Transport of spatter by argon gas flow	61
4.4.3	Theoretical considerations	64
4.5	Conclusion	65
5	Simulations of spatter transport by inert gas flow	67
5.1	Introduction	67
5.2	Numerical modelling	68
5.2.1	CFD	68
5.2.2	DPM	69
5.3	Simulation set-up	70
5.3.1	Mesh independence test	71
5.3.2	Boundary conditions	72
5.3.3	Initial conditions for spatter ejection profiles	72
5.4	Results and discussion	77
5.4.1	Mesh independence test	77
5.4.2	Validation with experiment results	77
5.4.3	Effectiveness of inert gas cross-flow	83
5.4.4	Limitations of current work	86
5.5	Conclusion	87
6	Conclusions & Future work	88
	References	90

List of Tables

2.1	List of AM processes	8
2.2	Large scale AM machines comparison	12
2.3	Tensile properties of AlSi10Mg parts manufactured from SLM	16
3.1	Chemical composition (weight %) of AlSi10Mg	28
3.2	2 ³ design experiment	29
3.3	Plus and Minus table for 2 ³ design experiment	30
3.4	ANOVA for the 2 ³ design experiment (UTS)	34
3.5	Chemical composition (weight %) breakdown obtained from a single powder particle	35
3.6	ANOVA for the 2 ³ design experiment (spatter)	37
4.1	Chemical composition (weight %) of AlSi10Mg	46
4.2	Statistical table for t-tests	59
5.1	Fluid properties and chamber settings	72
5.2	Parameters for molten droplet escape condition	81

List of Figures

2.1	CAD image (left) and AM part made out of IN718 (right) with internal structures for weight savings (Buchbinder et al., 2011)	7
2.2	(a) Schematic of LENS process (Keicher et al., 1997) and (b) LENS processing of hollow part (Palvcivc et al., 2009)	10
2.3	A typical SLM layout (Kruth et al., 2005)	11
2.4	SLM 500 HL machine by SLM Solutions GmbH (GmbH, 2015)	13
2.5	Aluminium chassis components manufactured by casting (Brungs, 1997)	14
2.6	Schematic of spatter ejection from melt pool and its transport by the inert gas flow (green arrows) in the $-x$ direction.	17
2.7	Powder accumulation on left side of SLM Solutions 500 HL build chamber	23
3.1	Local scanning strategy for inner regions in (a) $-x$ (b) $+x$ directions . . .	29
3.2	Layout of part placement	30
3.3	Sample of machined tensile specimen	31
3.4	Camera set-up placed outside SLM Solutions 280 HL build chamber observation window (computer not seen in image)	32
3.5	A: Mean UTS (MPa) and $\pm$ standard deviation in each run. B: Main effects plot for UTS (MPa).	33
3.6	Residual plots for UTS	34
3.7	SEM images of A: Fresh powder; B: spatter collected near the outlet observed; C: Single particle of spatter. D: Sample EDS result of single spatter.	35
3.8	SEM of fracture sites. A: A sample from run <i>abc</i> . B: A sample from run <i>b</i> . One could observe a with higher porosity (circled) and unmelted powder (arrow) in this run compared to run <i>abc</i>	36
3.9	Residual plots for mass of accumulated spatter	36
3.10	A: Mean mass of collected powder (g) and $\pm$ standard deviation in each run. B: Main effects plot for mass of collected powder (g)	37
3.11	Images extracted from video at intervals of $24 \mu s$. (a) Run <i>c</i> (b) Run <i>ac</i> . .	39
3.12	Schematic of laser beam scanning (a) in and (b) against the direction of the gas flow which might have caused the spatter in the latter case . . .	41

3.13	Normalised column graph for spatter accumulation outside of powder bed and UTS	42
4.1	SEM image of fresh AlSi10Mg powder	46
4.2	Layout of scanning region of 80×40 mm, with spatter on powder bed distributed on equal columns of 40×120 mm each. Red arrows indicate unidirectional laser scan vectors while green arrows represent inert gas flow. The scanning order was set from the top going downwards ($-y$ direction)	48
4.3	Image capturing set-up	49
4.4	Typical images obtained at the tenth layer: (a) before and (b) after laser scanning (post perspective transformation), (c) result of absolute difference between image (a) and (b), (d) after application of Renyi entropy thresholding. Figures (c) and (d) have a resolution of 1272×2544 pixels.	53
4.5	Plot of mean SP and standard deviation at different layer numbers for gas pump setting (a) 60 % and (b) 67 %.	54
4.6	Bar chart of mean of summed up pixels and standard deviation representing spatter particles for each column from A to D for the tenth layer.	55
4.7	Plot of mean of summed up pixels and standard deviation representing spatter particles for columns of 100 pixels width or 6.29 mm. The edge of the scanned region corresponds to $x = 0$ mark.	56
4.8	Bar chart of mean of summed up mass and standard deviation for each column from A to D.	56
4.9	Bar chart of mean diameter and standard deviation for each column from A to D.	57
4.10	Plot of percentage of spatter pixels against mass of spatter for regions D to A.	58
4.11	Plot of percentage of Stokes number for regions D to A. The characteristic length L_0 is taken from the center of the scanned region.	61
4.12	Schematic of spatter ejection profiles from melt pool and the effect of gas flow in the particle trajectories.	64
5.1	Schematic of spatter ejection from melt pool and its transport by the inert gas flow (green arrows) in the $-x$ direction. Spatter distribution in regions marked A to D will be the main areas of interest in this study.	68
5.2	(a) Actual front view SLM 280 chamber and (b) 3D domain used in simulations.	71
5.3	Spatter particle size distributions obtained experimentally (Anwar & Pham, 2018).	74

5.4	Initial ejection profiles of 30 hot spatter particles extracted from Bidare et al. (2017a).	75
5.5	Fitting of a normal distribution plot to the ejection angles of spatter particles which were experimentally observed.	75
5.6	Mesh independence test results for coarse, medium and fine meshed domains.	77
5.7	Steady state velocity contours on $x - z$ plane showing laminar and uniform argon gas flow near the powder bed for inlet velocity of 1.41 m/s. .	78
5.8	Profiles of path trajectories for a range of spatter particles for gas flow velocity of 1.41 m/s.	79
5.9	Bar chart of mean diameter of spatter particles for both experiment and simulations at (a) 60 and (b) 67 % of gas pump setting.	80
5.10	Plot of spatter ejection velocity against diameter.	82
5.11	Bar chart of mean mass percentage of spatter particles for both experiment and simulations at (a) 60 and (b) 67 % of gas pump setting.	83
5.12	Profile of path trajectories for a range of spatter particles without gas flow.	84
5.13	Bar chart of mean diameter of spatter particles from simulations.	85
5.14	Bar chart of mass percentage of spatter particles from simulations.	85

List of Publications

Submitted to Journal

- **Anwar, A. B.**, Ibrahim, I. H. & Pham, Q.-C. (2018b). Spatter transport by inert gas flow in Selective Laser Melting: A simulation study. *International Journal of Multiphase Flow*.

Journal Publications

- Abdul Jalil, S., **Anwar, A. B.**, Chou, S. M., & Tai, K. (2018). Material yield strain identification using energy absorption. *The Journal of Strain Analysis for Engineering Design*, 53, 463-469.
- **Anwar, A. B.**, & Pham, Q.-C. (2018b). Study of the spatter distribution on the powder bed during selective laser melting. *Additive Manufacturing*, 22, 86-97.
- **Anwar, A. B.**, & Pham, Q.-C. (2017). Selective laser melting of AlSi10Mg: Effects of scan direction, part placement and inert gas flow velocity on tensile strength. *Journal of Materials Processing Technology*, 240, 388-396.

Conferences

- **Anwar, A. B.**, & Pham, Q.-C. (2018a). Spattering phenomenon in selective laser melting: A review of spatter formation, effects and countermeasures. *Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018)*, 3, 541-546.
- **Anwar, A. B.**, & Pham, Q.-C. (2016). Effect of Unidirectional Scanning with Respect to Gas Flow on Spattered Powder Formation During Selective Laser Melting of AlSi10Mg. *Proceedings of the 2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016)*, 2, 531-536.

Chapter 1

Introduction

1.1 Motivation

Additive Manufacturing (AM) or more commonly known as 3D printing has been developing rapidly in recent years especially in the aerospace and automotive industries. Selective Laser Melting (SLM) is one of the many available AM processes for the fabrication of customised and complex parts, where much advanced research and development is being made. Current SLM research mainly focuses on the optimisation of input parameters for available materials (mainly metal and its alloys), manufacturing using new and multiple materials, simulation and numerical modelling, various testing on applications and also on the scale of the process.

As of now, the dimensions of printable parts are limited by the sizes of currently available machines. For larger parts to be produced, there is a need to develop even bigger machines. Thus, it is critical that the present hindrances associated with large scale AM are effectively tackled in order to realise this possibility. Large scale SLM is limited by factors such as the maximum weight of material powder the machine can sustain, the number of lasers in the machine and also the effective uncontaminated powder bed area for scanning. For the latter to be achieved, it is necessary to investigate the effects and also depositions of SLM by-products on the powder bed, especially spatter particles.

Laser powder bed fusion processes such as SLM tend to emit unwanted contaminants such as plasma plume, metal vapour and more observably, spatter particles. These particles are distinguished by their darker appearance and significantly larger sizes. Their presence on the powder bed introduces uneven layer thickness and acts as pore inducing regions within the final printed part. Nonetheless, other undesirable effects of spatter-ing, specifically on its interactions with the inert gas flow were yet to be discovered.

Generally, spatter particles are eliminated with the introduction of an inert gas flow which is pumped transversely from one side of the SLM chamber to the other. In spite of this, traces of spatter are still observed during the laser scanning of the powder bed as

indicated by their darker presence as compared to the fresh or virgin powder. A possible immediate tool to assess the distribution patterns could also be explored. Characterisation of the spatter deposition on the powder bed was identified as a possible measure to validate the effectiveness of the inert gas flow. Such data could serve as the ground truth for simulation studies, as reported later on in this thesis.

Therefore, it is postulated that these studies would facilitate a deeper understanding of the spattering effects and more importantly on the development of a more effective gas flow system capable of transporting spatter particles over a further distance. Only then would it be possible to fabricate larger SLM parts.

1.2 Objectives & Scope

The overall aim of this thesis is to further understand the effects and removal of spatter particles by the inert gas flow during SLM. To achieve this, three main objectives were set throughout the course of this PhD study. The first was to investigate the effects of possible laser-spatter interactions on the properties of the printed parts. Three factors were varied to analyse their effects on the mechanical properties of printed parts. They comprised of laser scanning direction parallel to the gas flow direction, part location on the substrate and inert gas flow velocity. The interactions were also investigated visually.

Secondly, spatter distributions on the powder bed at different gas flow velocities were to be analysed. The main objectives were to characterise the mass and size distribution of deposited spatter downstream of the inert gas flow. The experimental data were to be used as ground truth for the simulations.

The final objective was to perform simulations on the spatter trajectories and their eventual deposition on the powder bed, under the influence of the inert gas flow. Another objective was to propose suitable spatter ejection profiles which would give good agreement with the earlier experimental results. The final objective was to study the spatter distributions without any inert gas flow, an impossibility in the real commercial machines.

1.3 Contributions

Three major contributions are presented in this thesis which successfully achieved the main objectives as mentioned earlier. They are briefly elaborated in the following subsections.

1.3.1 Effects of laser-spatter interactions in SLM

One of the objectives of the first experimental study was to explore whether possible laser-spatter interactions took place under the influence of the inert gas flow. Previously, other studies reported on the detrimental effects of the presence of spatter particles on the powder bed.

The SLM Solutions 280 machine was used as the experiment set-up with argon as the inert gas. Aluminium alloy, AlSi10Mg, was chosen as the material for the experiments due to its wide applications in the aerospace and automotive sectors. To test the properties of the samples collected, the Ultimate Tensile Strength (UTS) was chosen and the corresponding data was obtained for each ASTM E8 tensile specimen. Scanning Electron Microscopy (SEM) and Energy-Dispersive x-ray Spectroscopy (EDS) was applied during analysis of spatter particles accumulated outside of the powder bed, near the outlet region. In this study, laser-spatter interactions above the powder bed were captured for the first time on a high speed camera. Such interactions which appeared as abnormally bright sparks were attributed to be the main cause of the significantly varying UTS of the printed parts, since energy was wasted during the burning of spatter particles which were blown into the paths of the laser beam by the inert gas flow. It was also recommended that laser scanning was done in the direction of the gas flow to minimise the laser-spatter interactions. The findings of the study has been published in the "Journal of Materials Processing Technology".

Additionally, the printed specimens were subjected to tensile tests, and the results were applied to another study which does not form part of this thesis. The research conducted for the mentioned work has been published in the "Journal of Strain Analysis for Engineering Design" and is found in the Appendix section of this thesis.

1.3.2 Spatter distribution on the powder bed

With respect to the spatter particles on the powder bed, the mass and size distributions were characterised. The Stokes (Stk) number was then used as a parameter to observe the gas flow effectiveness in the spatter transport, which accounts for particles suspended in the gas flow. Image processing was also applied in order to immediately characterise the spatter distribution on the powder bed.

There are three major sub-contributions as part of this second experimental study. Firstly, we proposed a simple camera set-up applied to provide an immediate assessment of the spatter distribution on the powder bed. The processed images that were captured were then compared to the mass distribution characteristics, giving a moderate positive linear relationship. For the second part, spatter mass and size has been reported to be the largest, close to the scanning regions while decreasing gradually downstream of the gas flow. The increase in gas flow also resulted in heavier particles being removed towards

the chamber outlet. Finally, the Stk number computations provided scientific reasoning for the limited width of the SLM Solutions machines, which is currently restricted to 280 mm. The study on the powder bed spatter distribution has been published in the "Additive Manufacturing" journal.

1.3.3 Effectiveness of inert gas flow in spatter removal

The last contribution of this thesis involve the simulation studies on the spatter particle trajectories within the chamber of the SLM 280 machine. The three-dimensional simulations were then conducted on the Computational Fluid Dynamics (CFD) software, ANSYS Fluent using the Eulerian method. The domain was reduced to a portion of the actual size of the SLM 280 chamber. Ejection profiles of the spatter particles were based on the vapour entrainment effects. The Discrete Phase Model (DPM) was applied to track the particles using the Lagrangian method. Particle-particle interactions were neglected. Vapour entrainment and recoil pressure were reported as the main ejection mechanisms of spatter particles, which could be both hot and cold. However, the simulations accounted for only the entrainment driven effects as being responsible for the ejection of the spatter particles.

The results showed good agreement with the earlier experimental work. The effectiveness of the argon gas flow in removing the spatter particles was very limited since the particles mainly travel on their own trajectories owing to their high initial momentum. It is worth noting that the experimental data showed orthogonal distribution (along the y direction). Since the ejections were initialized in the $x - z$ plane, minimal penetration was observed in the y , especially due to the laminar flow of the argon gas in the $-x$ direction. Nonetheless, optimisation of the gas flow system of large scale SLM Solutions machines can be achieved using the simulated ejection characteristics of this study. The manuscript for the simulation work has been submitted to the "International Journal of Multiphase Flow".

1.4 Thesis Outline

This thesis consists of 6 chapters including this introductory chapter. The rest of the chapters are briefly elaborated as follows.

In Chapter 2, we review literature on the SLM of AlSi10Mg as well as the issues with respect to the spattering phenomenon. This chapter identifies the research knowledge gaps for spattering in SLM and elaborates how our contributions fit in the grand scheme of things.

In Chapter 3, we captured laser-spatter interactions for the first time during SLM with the use of a high-speed camera. Their effects on the UTS of the printed parts were

quantified and statistically analysed using the Analysis of Variance (ANOVA). Following this, the second major research focused on the spatter distribution on the powder bed, in Chapter 4. We quantified the mass and size distributions downstream of the inert gas flow. The corresponding Stk number analysis provided insights into the limitations of the current commercial SLM machines by SLM Solutions. Using the ground truth results established earlier, simulations of spatter transport by the inert gas flow are presented in Chapter 5. We performed CFD simulations with the DPM to solve for the trajectories of the spatter particles during flight. The results were then validated by the earlier experimental data obtained.

Finally, we conclude this thesis in Chapter 6.

Chapter 2

Literature Review

The literature review in this thesis evaluates the work that has been done in large scale AM, specifically the SLM of AlSi10Mg, and the formation, effects and countermeasures of the spattering phenomenon. The review on the mentioned aspects with regards to spattering has been published in the 3rd International Conference on Progress in Additive Manufacturing, 2018.

2.1 Additive Manufacturing

In the 1980s, AM was formerly known as Rapid Prototyping (RP) when highly customised and complex prototype parts were created to have a physical feel of the final designed product and also for testing purposes (Wong & Hernandez, 2012). Advantages of RP included time and costs savings in terms of manufacturing complicated parts, as compared to other conventional methods. At that time, such parts were not made to be used as a final product, due to the lack of technological advancements necessary to introduce functionality with the desired precision in terms of appearance and mechanical properties. Recently, the American Society for Testing and Materials (ASTM) International formed a technical committee (ASTM F2792) which defined AM as an official industry term which refers to "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (Gibson et al., 2009). Other commonly used terms include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer based manufacturing, freeform fabrication and 3D printing (Associates, 2015). It has also been claimed that the rapid emergence of AM as a highly customised manufacturing technique has potentially created a new type of industrial revolution, in the same manner the internet has changed the way information is made available and distributed to the masses (Bogue, 2013).

The fundamental mechanism behind AM lies in the layer by layer method of manu-

Figure 2.1: CAD image (left) and AM part made out of IN718 (right) with internal structures for weight savings (Buchbinder et al., 2011)

facturing (Huang et al., 2012a). A 3D Computer Aided Design (CAD) model is first obtained and converted to a standard Stereolithography (STL) file where the model is sliced into the desired layer thickness. In this step, the build time is also estimated following the placement of parts, input of process parameters and addition of support structures into the file. The machine is then set up for printing which then proceeds autonomously. When the build job is done, the part is removed and subjected to post processing (if necessary) for future applications (Gibson et al., 2009).

Technological advancements have brought about a wave of AM methods for fabricating parts for a wide range of materials. A compilation of some of the available AM techniques and their corresponding processed materials is listed below in Table 2.1 (Frazier, 2014; Huang et al., 2012b; Kruth et al., 1998):

Applications of AM can be found in the automotive, aerospace, biomedical and more recently the electronics industries, where both cost and time could be lower than parts manufactured by conventional methods (Kruth et al., 1998; Melchels et al., 2012; Uriondo et al., 2015). Other advantages include the possibilities of manufacturing complicated and customised parts which would otherwise be very difficult, such as architectural and archaeological modelling in stereolithography and honeycomb cells (Wong & Hernandez, 2012; Zhang et al., 2015a). The diminishing costs of 3D printer hardware, software and materials for processing has also made it possible for innovators to generate low cost machines for commercial and domestic purposes (Gao et al., 2015). However, AM of ceramics has seen success to a limited extent and the manufacturing of plastics in high strength applications is also not practical, leading to a surge in the research for metal-based manufacturing (Kumar & Pityana, 2011). The research for this PhD focuses on metal-based AM, which will be reviewed in the next subsection.

Table 2.1: List of AM processes

Process	Materials	Systems
Powder Bed		
Three dimensional printing (3DP)	Ceramic, Metal, Polymer (all with binder)	Soligen, Extruhone, Z-corp
Electron Beam Melting (EBM)	Metal	Arcam
Selective Laser Sintering (SLS)	Nylon, Metal, Ceramic, Paraffin wax, Polymer, Sand	EOS M280, 3D Systems Sinterstation HiQ
Laser Powder Bed Fusion (LPBF)	Metal, Ceramic	Concept Laser, MTT, SLM Solutions, Phenix System Group PXL, Renishaw, Realizer, Matsuura lumex
Powder Feed		
Direct Energy Deposition (DED)	Metal	Optomec LENS 850-R
Liquid		
Fused Deposition Modelling (FDM)	Polymer, Wax, Filled Polymer, Metal and Ceramic with binder	Stratasys
Ink jet Printing (IJP)	Polymer, Wax	3D Systems
Stereolithography (STL)	Photopolymer: acrylates, epoxies, filled and coloured resins	3D Systems, NTT Data, Cubital
Gas		
Selective Laser Chemical Vapour Deposition (SLCVD)	Metal, Ceramic	LCVD, SALD

2.1.1 Metal-Based Additive Manufacturing

As seen in Table 2.1, a wide range of metal-based AM processes have been developed. This part of the report will discuss further on some of the research that has been carried out with regards to the manufacturing processes and how it is relevant in the development of large scale metal-based AM machines. In this review, one solid based and four powder based methods that are considered include LOM, SLM, SLS, and LENS. The main areas of research for each process; process optimization, feedback control and monitoring, printing using new materials, simulation and modelling will be discussed wherever applicable.

LENS

Unlike LOM, LENS is a type of powder feed AM capable of forming fully dense metal parts *directly* from CAD models (Dahotre & Harimkar, 2008). This process comprises of a high power fiber Nd:YAG laser, a three axis computer positioning system and a powder feed unit all enclosed in an inert argon gas atmosphere to minimize oxidation and for safety reasons (Atwood et al., 1998). The powder is supplied through a nozzle

under gravity or pressurized carrier gas and deposited onto the build plate. The laser is focused to a small spot by one or more lenses and melts the powder into the shape desired. This cycle is repeated until the part is completed. There are also two types of powder feed systems, one where the deposition head moves and the build plate is stationary, and vice versa (Frazier, 2014).

LENS has been designed specifically for the fabrication of metal parts. A range of materials have been experimented on using LENS; stainless steel, nickel based alloys, titanium alloys, copper alloys and tooling steel, some of which showed good biocompatibility (Balla et al., 2009; Espana et al., 2010; Wong & Hernandez, 2012). Kummailil et al. (2005) has also conducted experiments on the effect of input parameters on Ti-6Al-4V deposition and concluded that mass flow rate and scan velocity as significant factors to deposition. The dimensions (in inches) of the deposit ranges from 0.005 to 0.040 thickness and 0.040 to 0.160 wide (Mudge & Wald, 2007). Finite element models of the LENS process has been developed by Wang et al. (2008) and Ye et al. (2006) which showed good agreement with experiments in terms of the thermal cycles and cooling rate of the melt pool, which determines the final microstructure and porosity and hence the mechanical properties of the final part such as fatigue behaviour (Prabhu et al., 2015).

LENS has also proven to be an effective solution for repair applications, due to the minimal distortions experienced as a consequence of the small heat affected zone (HAZ) and typical columnar grain growth in the deposit (Wu et al., 2004). This was demonstrated by Mudge & Wald (2007), where a Ti-6Al-4V bearing housing from a gas turbine engine was repaired with insignificant distortion and subjected for testing in an engine, saving several weeks of downtime. The potential of LENS as a manufacturing and repair method has also been demonstrated, especially for aerospace components such as Inconel 625 and other functionally graded materials (Islam et al., 2001; Li, 2006; Liu & DuPont, 2003). Other benefits include the closed loop control system to control the volume of melt pool, video measuring system and non-contact surface analyzer, as claimed by Sandia National Laboratories (Laboratories, 2014).

Overall, LENS is capable of producing metal-based parts for aerospace applications and the potential to make large parts as compared to other AM processes (May, 2017). However, the requirements of this project has made it necessary to work on SLM as the main AM technique. Powder bed AM specifically SLM will be discussed next.

SLS/SLM

In the build chamber of an SLM machine where inert gas (argon or nitrogen) is pumped in, a high powered fiber laser (usually Nd:YAG laser up to 1 kW) scans a cross-sectional area of a part on the powder bed with pre-defined layer thickness (20 to 100 μm), causing the powder to melt. Subsequently, the build platform is lowered and another layer of powder is evenly spread across it. The sintering/melting of the successive cross-sectional

Figure 2.2: (a) Schematic of LENS process (Keicher et al., 1997) and (b) LENS processing of hollow part (Palvcivc et al., 2009)

area by laser scanning is then performed. When a layer of molten cross-sectional area solidifies, it bonds to the layer directly above it, forming a three-dimensional part. This cycle continues and the whole process is complete when the last cross-sectional area has been scanned, producing the full desired part (Lott et al., 2011; Seidel et al., 2014). In SLM, full melting is achieved for the material, forming a completely molten pool which solidifies to form near full dense objects (Kruth et al., 2005). This is slightly different from SLS, where the powder is heated to a temperature below melting point, reducing the surface energy and fusing the particles without actual melting (Dahotre & Harimkar, 2008; Kruth et al., 2003).

Much research and development has been made in SLM, mainly regarding the optimization of parameters for manufacturing parts using different types of metals and alloys (Gu et al., 2012; Kruth et al., 2004; Read et al., 2015; Rombouts et al., 2006; Song et al., 2014; Sun et al., 2013). Some of the main input parameters include the laser power, laser type, scanning velocity, laser beam spot size, hatching styles, powder layer thickness, scan-

Figure 2.3: A typical SLM layout (Kruth et al., 2005)

ning strategies, preheating temperature of the base plate etc (Leuven, 2007; Loh et al., 2014). Environmental effects such as inert gas and preheating and have also been studied (Zhang et al., 2013a). Parameter optimization seeks to minimise unwanted effects on the final part. Such effects comprise of high residual stress causing structural deformation (Wu et al., 2014), balling effects (Tolochko et al., 2004; Zhou et al., 2015), porosity (Qiu et al., 2015), staircase effects and irregular melting of overhanging regions (Yasa et al., 2011). More recently, modelling of the SLM process have been performed, to account for the various conditions during the melting process, such as material evaporation and shrinkage, heat transfer and stability of single scan tracks (Childs et al., 2004; Gusarov & Smurov, 2010; Gusarov et al., 2007; Loh et al., 2015; Teng et al., 2017). Process monitoring, sensing and feedback control for melt pool formation has also been in the works (Chivel & Smurov, 2010; Craeghs et al., 2010; Doubenskaia et al., 2010; Krauss et al., 2012; Kruth et al., 2007; Lott et al., 2011; Scime & Beuth, 2018a,b). Experimental indicators for parts produced include tensile strength, Young's modulus, hardness, porosity, density and surface roughness. All these research seeks to improve the SLM process either using self made or commercially available machines with limited build volume. Thus, not much progress has been made in terms of large scale or upsizing the build volumes of the SLM machines which would definitely be beneficial in the manufacturing of large, complicated metal parts.

To conclude, the current research and development focuses more on process optimisation using *currently available* machines, rather than developing large scale SLM machines, due to the many complications that are associated with the SLM process as mentioned earlier. This is where the current research comes in to fill the gap.

2.1.2 Large Scale AM

A range of AM machines and their build volumes, together with system type (powder bed, powder feed and wire feed) have been reviewed (Frazier, 2014). A comparison of large scale SLM machines available in the market is shown in table 2.2 (eos, 2015; GmbH, 2015; Laser, 2015). Larger scale methods such as LENS and LOM either lack the precision and accuracy or occupy large spaces as compared to powder bed manufacturing. Since there is a lack of research in large scale SLM, the overall objective of this PhD is to investigate the challenges with regards to constructing an SLM machine suitable for larger scale manufacturing. As mentioned earlier in chapter 1, the scope of this thesis involves the study of spattering effects and also their deposition on the powder bed under the influence of the gas flow.

Table 2.2: Large scale AM machines comparison

Type	Machine Model	Dimensions in x,y,z (mm)	Build Volume (mm ³)
Powder bed	SLM Solutions SLM 800	280 x 500 x 850	1.19×10^8
	SLM Solutions SLM 500	280 x 500 x 325	4.55×10^7
	EOS M 400	400 x 400 x 400	6.40×10^7
	Concept Laser X line 1000R	630 x 400 x 500	1.26×10^8
	Concept Laser X line 2000R	800 x 400 x 500	1.60×10^8
Powder feed	Optomec LENS 850-R	900 x 1500 x 900	1.22×10^9
Wire feed	Sciaky EBAM	2692 x 1194 x 1600	5.14×10^9

Figure 2.4: SLM 500 HL machine by SLM Solutions GmbH (GmbH, 2015)

2.1.3 SLM of AlSi10Mg

Traditionally, casting of aluminium alloys has been used in the automotive industry to achieve highly customised and thin walled parts which would otherwise be time consuming and complex to manufacture. A number of casting technologies are available such as vacuum, squeeze, Thixo and high pressure die casting for producing vehicle parts (Brungs, 1997; Cole & Sherman, 1995). Other favourable properties include low density, high strength, good corrosion resistance, excellent weldability, high hardenability and reflectivity (Aboulkhair et al., 2014; Bland & Aboulkhair, 2015).

With the rise of AM, the SLM of aluminium alloys, specifically AlSi10Mg and AlSi12 has been studied due to the relative ease of processing since the difference in the liquidus and solidus temperatures is slight as compared to high strength aluminium wrought alloys (Bartkowiak et al., 2011). In other words, the melting and solidification points are close such that the molten pool does not remain liquid for long. As a result, parts with exceptionally fine microstructure and controllable texture can be obtained when the right process parameters are applied (Thijs et al., 2013). All these properties make aluminium alloys favourable manufacturing vehicle parts in the automotive and aerospace industries.

Cross Beam-Front
Side Parts-Rear

	Cross Beam	Side Part
Alloy:	GD- AlSi10Mg T6	GD- AlSi10Mg T6
Process:	Vacuum HPDC	Vacuum HPDC
Wall-Size:	2,5 - 5 mm	2,5 - 4 mm
Dimensions:	800 x 600 mm	350 x 300 mm
Weight:	4,0 kg	1,5 kg

Figure 2.5: Aluminium chassis components manufactured by casting (Brungs, 1997)

Process optimization of aluminium alloys using SLM has been studied by many researchers (Buchbinder et al., 2011; Canali, 2015; Li & Gu, 2014; Liu et al., 2010; Louvis et al., 2011; Olakanmi et al., 2015; Read et al., 2015). AlSi10Mg parts with density as high as $99.77 \pm 0.008 \%$ have been manufactured with scan speed of 500 mm/s, hatch spacing of 50 μm , 100 W laser power and a layer thickness of 40 μm with pre-sinter scan strategy, as reported by Aboulkhair et al. (2014). However, metallurgical pores which can be categorised by size and morphology have been seen to form at lower scan speeds, are controlled the energy density transferred to the powder during scanning (Bland & Aboulkhair, 2015). Mg is also more susceptible to evaporation and scattering, as observed in the analysis of spatter. The contamination of Mg oxides could potentially affect the mechanical properties of parts formed (Aboulkhair et al., 2014). A table of the tensile properties as a result of varying the SLM parameters is shown in Table 2.3, where P is the laser power, v is the laser speed, t is the layer thickness and h is the hatch spacing.

AlSi10Mg parts have also demonstrated comparable or superior properties than their casted counterparts in terms of hardness, UTS, elongation, impact energy (Van Humbeeck et al., 2013). SLM AlSi10Mg specimens studied by Buchbinder et al. (2011) showed a hardness value of 145 HV, approximately 200 % higher than the die casted parts. Effects of build orientation in the horizontal and vertical planes in the SLM process chamber have also been studied by Buchbinder. It was found that z-oriented parts showed the

lowest tensile strength at 360 MPa as compared to horizontally (0° to plate with highest UTS of 420 MPa) and diagonally (45°) placed parts. These results show good agreement with Kempen et al. (2012) and concluded that elongation at break is affected by z parallel part, due to the optimal density scanning strategy which causes z-oriented tensile samples to form more borderline porosity. These pores make the z-oriented tensile parts more sensitive to crack initiation, compared to x and y oriented tensile samples. Scan tracks were also shorter for z parallel part. Pores are detrimental to the part properties as they act as crack initiation sites where the crack propagation accelerates, leading to failure of the part (Murakami & Endo, 1994). Tang & Pistorius (2017) and Beretta & Romano (2017) reported that the fatigue life of AlSi10Mg parts were comparable to those fabricated by conventional casting. The defects present were relatively larger, due to the formation of oxides associated with vaporised metal. To optimise the fatigue resistance, a framework was proposed to model the high cycle fatigue resistance in the presence of defects in AlSi10Mg parts produced by SLM (Romano et al., 2018). It was shown that the model successfully described the experimental scatter since the distribution of initial defect size of the samples were evaluated.

The formation of the pores in AlSi10Mg parts is partially attributed to the effect of oxidation. The presence of oxygen inside the build chamber leads to oxidation of the top of the melt pool which is vaporised under the laser, creating fumes of oxide particles. Melt pool stirring probably due to Marangoni forces broke up the oxide at the base of the melt pool causing fusion to the underlying tracks. Oxides at the sides of the melt pool remained intact, creating regions of weakness and porosity as the melt pool failed to wet the surrounding material. Pores form due to oxide films between laser hatches at every layer of the aluminium part (Louvis et al., 2011). Oxygen also plays a significant role in contributing to unwanted effects during scanning such as spatter formation and this will be explained in the next section.

2.2 Spatter in SLM

In the build chamber of an SLM machine where inert gas (argon or nitrogen) is pumped in, a high-powered fiber laser (usually Nd: YAG laser up to 1 kW) scans a cross-sectional area of a part on the powder bed with pre-defined layer thickness (usually 20 to 100 μm), causing the powder to melt. Subsequently, the build platform is lowered and another layer of powder is evenly spread across it. The melting of the successive cross-sectional area by laser scanning is then performed. When a layer of molten cross-sectional area solidifies, it bonds to the layer directly below it, forming a three-dimensional part. This cycle continues and the whole process is complete when the last cross-sectional area has been scanned, producing the full desired part. Much research has been performed with respect to the optimisation of the SLM process to produce parts of high quality and

Table 2.3: Tensile properties of AlSi10Mg parts manufactured from SLM

P [W]	v [mm/s]	t [μm]	h [μm]	Build orientation	YS [MPa]	UTS [MPa]	ϵ [%]	Ref.
175	1025	30	97.5	Horizontal	252 ± 18	340 ± 38	1.3 ± 0.8	(Read et al., 2015)
175	1025	30	97.5	Vertical	231 ± 9	317 ± 46	1.1 ± 0.4	
200	1400	30	105	Vertical	-	396 ± 8	5.55 ± 0.4	(Kempen et al., 2012)
350	1140	50	170	Horizontal	322.17 ± 8.1	434.24 ± 10.7	5.3 ± 0.2	(Li et al., 2016)
200	570	25	130	-	268 ± 2	333 ± 15	1.4 ± 0.3	(Aboulkhair et al., 2016)
370	1300	30	190	Horizontal	-	357 ± 3	4.6	(Ch et al., 2019)
370	1300	30	190	Vertical	-	385 ± 5	4.5	
370	1300	30	190	Horizontal	264 ± 4	452 ± 1	3.6 ± 1	(Girelli et al., 2019)
370	1300	30	190	Vertical	247 ± 1	482 ± 1	6.5 ± 0.3	
350	1170	50	240	Vertical	300	455	4.5	(Chen et al., 2017)
175	1025	30	97.5	Horizontal	265	375	2.7	(Tradowsky et al., 2016)
175	1025	30	97.5	Vertical	225	295	1.6	
400	1000	25	175	Horizontal	-	358	7.4	(Wang et al., 2018)
400	1000	25	175	Vertical	-	334	3.6	
240	500	50	200	Horizontal	245	420	5.9	(Buchbinder et al., 2015)
240	500	50	200	Vertical	220	400	3.2	

appearance. Despite this, there are still some challenges which include delamination due to warpage, high surface roughness and the inevitable spatter generation and their subsequent distribution on the powder bed.

During SLM or any other laser-based materials processing method, the spattering phenomenon occurs, which refers to the ejection of particles from the melt pool. Such particles would often deposit near the processing regions on the workpiece and in the case of SLM, the powder bed. As mentioned earlier, the introduction of the inert gas flow into the processing chamber is partly to prevent such particles from depositing on the powder bed, in order to minimise contamination.

2.2.1 Formation and Characteristics of Spattering Phenomenon

Similar to laser welding and drilling, the melt pool mechanisms have been attributed to be responsible for the ejection of molten material. Qiu et al. (2015) reported that the Marangoni forces coupled with the recoil pressure significantly contributes to the melt pool instability and eventual spattering during SLM. This is illustrated in Fig. 5.1 where the high recoil pressure originates from the downward force exerted by the rapid expansion of the metal vapour directly above the melt pool. Using a three-dimensional

high fidelity power scale model, which takes into account the multi-physics of the melt pool flow, Khairallah et al. (2016) successfully demonstrated how the recoil pressure overcomes the surface tension of the melt pool leading to the formation of spatter.

In-situ observations recorded by Matthews et al. (2016) have shown that the entrainment of particles by surrounding gas flow has also resulted in the denudation of powder layers. More recent experimental evidence from the use of high speed cameras with a frame rate of 100kfps have revealed a more dominant cause of spatter generation confirming the work done by Matthews et al. (2016). In the work conducted by Ly et al. (2017) on the SLM of stainless steel 316L and titanium alloy Ti6Al4V, it was observed that the upward motion of the vapour jet generates a low-pressure region above the melt pool causing an inward motion of the surrounding gas flow. Due to this metal-vapour flow entrainment, a significant number of particles were accelerated away vertically upwards and towards the rear, relative to the direction of scanning. Simulations were also performed and it was shown that the entrainment velocities are inversely proportional to the density of the particles. The researchers also identified three different types of spatter ejected, depending on their individual generation mechanisms. The type of spatter most commonly observed and studied by other researchers would be the molten spatter, which can be seen as sparks during the SLM process. Such ejected molten material was recorded to have ejection velocities from 3 to 8 m/s and form 15 % of all spatter generated. Additionally, hot ejections formed 60 % while the remaining 25 % comprised of cold ejections. Also more recently, the ejection velocities at different regions around the local laser processing area at the powder bed varies. Particles accelerated by the vapour jet are ejected at a order of magnitude higher than those by the induced argon gas flow (Guo et al., 2018).

However, Matthews et al. (2016) reported that at high pressures near the melt pool, the Knudsen number would be small (<1) and this results in the high-speed metal vapour flux which induces the surrounding gas flow, eventually leading to entrainment. On the

Figure 2.6: Schematic of spatter ejection from melt pool and its transport by the inert gas flow (green arrows) in the -x direction.

other hand, at low pressures where the Knudsen number is higher (>1), the metal vapour expands laterally, pushing the powder particles away from the melt pool. Their work was further validated by Bidare et al. (2018a), who showed that at sub-atmospheric pressures, in the molecular flow regime, particles were repelled by the laser plume away from the melt pool, instead of being entrained. On the contrary, at high pressure atmospheres, the entrainment of powder particles in the flow of the shielding gas due to the generation of the laser plume were observed. Denudation of the powder bed was also reduced regardless of the use of argon or helium gas (Bidare et al., 2018b). This shows that the spatter formation is indeed affected by the surrounding vapour pressure.

The studies performed by Ly et al. (2017) is further validated by Bidare et al. (2017a) where schlieren imaging was applied in an open architecture system for flow visualisation of spatter-gas interactions above the melt pool. It was shown that spatter generation shifted from the front to the rear when laser power and scanning velocity was increased. Aerodynamic drag by the plasma plume acting on particles being ejected upwards caused them to be pulled towards the laser beam. As a result, the laser-spatter interactions generated particles which were sintered or melted before continuing on their individual trajectories. Due to the sintering and melting effects, agglomeration and fusion of particles were also reported leading to the formation of even larger spatter.

The amount of spatter generated is also influenced by the energy input, which is mainly governed by the laser power, scanning speed, layer thickness and hatch spacing. Andani et al. (2017b) characterised the spatter of aluminium alloy AlSi10Mg by varying the laser power and speed. It was shown that a reduction in spatter was achieved by decreasing laser power and increasing speed. However, the lower energy resulted in the incomplete melting of fresh powder and subsequently printed parts of lower quality, thus deeming the trade-off undesirable. Liu et al. (2015) also showed that increasing the energy input led to more intense spatter generation in terms of size, scattering and also jetting height during the SLM of stainless steel 361L.

According to a study on the microstructure of spatter done by Simonelli et al. (2015), regardless of the material used in SLM, spatter appeared to be spherical and also larger in size as compared to the fresh powder. Selective oxidation occurred on the surface of the spatter, leading to the formation of oxide layers up to several micrometers thick more significantly for material powder containing elements with high affinity to oxygen such as Mn, Si and Mg. The oxidized layers also give the particles a darker shade in appearance, making them easy to identify as illustrated in Figure 1.

Using a high speed camera of 500 fps, Wang et al. (2016) reported that the appearance of spatter is very distinct and also characterised three different types of spatter; metallic jet, droplet spatter and lastly powder spatter. SEM results revealed the unique morphologies for each type of spatter. The type I-metallic jet spatter appeared to be the most regular and spherical in shape, with minimal fresh powder or particle attachments

to it. The spherical uniformity decreases for type II-droplet spatter and even more drastically for type III-powder spatter, both of which had more particle attachments. The reason for the distinct features between the different spatter types are their origin positions or generation mechanisms.

2.2.2 Effects of Spattering

The effects of spatter are both cosmetic and detrimental to the part's properties, which could potentially lead to part failure. For example, it was discovered that the difficult removal of overlapped spatter between holes made using laser percussion drilling, caused superficial degradation to the workpiece and also the hole geometries Low et al. (2000a). Thermal gradients that arise when a spatter lands on a colder region of the weld metal would act as a localized stress raiser serving as crack initiation sites Otegui et al. (1989).

It has been widely reported that spatter on the powder bed will eventually lead to lower quality parts being printed, due to the introduction of inclusions and pores by the incomplete melting of the spatter particles, as investigated by Liu et al. (2015). Tensile tests were conducted for parts manufactured using fresh and contaminated powder with the latter producing significantly inferior results. This is largely due to the increased energy required to completely melt the spatter particles on the powder bed. A sample SEM image of spatter particles is shown in Figure 2 where their diameters are at least approximately 100 μm . Also the layer thickness is inversely proportional to the energy input. Thus, the accumulation of spatter on the powder bed will inevitably reduce the energy intended to melt the fresh powder. Another effect due to the larger size of spatter is the protrusion into the subsequent fresh powder layer. As a result, the motion of the recoater in laying the fresh powder might get disrupted, causing even more heterogeneity in the layer thickness. Another effect of spatter is the lack of fusion between scanned tracks as studied by Darvish et al. (2016), during the SLM of CoCrMo alloy.

Laser energy could also be wasted on burning the suspended spatter (beam scattering), leading to lower energy input at the powder bed for scanning. This effect has been demonstrated in the study performed by Anwar & Pham (2017), where the scanning direction and therefore the general direction of spatter generation leading to laser-spatter interactions, was shown to significantly affect the ultimate tensile strength (UTS) of the printed parts. The effect of increasing gas flow also resulted in higher UTS. This is possibly due to the decrease in porosity and then increase in density due to the greater removal of spatter.

2.2.3 Countermeasures

To overcome or minimise the effects of contamination by spatter on the powder bed, inert gas is pumped into the chamber as seen in Figure 3. In a typical commercial SLM

machine, the gas flows from one side of the chamber to the outlet at the opposite side. However, the effectiveness of the flow in transporting the undesirable particles is often not optimised.

It has been proven that flow uniformity close to the powder bed region is needed to improve the consistency and uniformity of part properties such as compression strength and density as reported by Ferrar et al. (2012). A reduction of 26.6 % in spatter accumulation was also achieved by Philo et al. (2017) by improving flow uniformity by 21.1 % through iterative design of the gas inlet. Ladewig et al. (2016) also showed that powder bed regions with low inert gas flow velocity led to the re-deposition of SLM by-products. Thus, it was recommended that homogeneous gas flow that is close to the powder bed should be achieved in order to minimise contamination.

The effects of the type of inert gas used have also been investigated. Wang et al. (2014) concluded that the type of gas used did not affect the part density or hardness, with a high density of 97 % achieved. However, parts built using helium gas had inferior mechanical properties, which could be attributed to the formation of pore clusters in the microstructure. As compared to conventionally manufactured parts, the SLM parts showed 1.5 times the yield strength, and up to 20 % higher UTS and twice the elongation to failure. Dai & Gu (2015) performed experiments and simulations to study the effect of the gas on metal vaporization behaviour. It was found that when argon gas was used, the melt pool depth reached a stable state due to a uniform recoil pressure as exhibited by the upwards direction of the evaporated material. Thus, a sound surface morphology is achieved. This is as opposed to the case of nitrogen gas, where humps in the top surface emerged as the vapour tends move towards the front of the laser beam during scanning. Hence, research has shown that the type of gas chosen is critical in the surface finish of the final part. However, in both cases, the direction of gas flow was not specifically stated. This could prove to be a fundamental parameter in the movement and deposition of vapour material, and more importantly, the accumulation of spatter.

On the other hand, Zhang et al. (2013b) investigated SLM of pure Ti under vacuum (0.0001 bar in reality) using a self-developed SLM machine, which was claimed to remove the gas expansion during scanning of the powder bed. Unfortunately, the observations of spatter under vacuum conditions were not documented. The use of pulse shaping in SLM has shown to reduce spatter ejection during processing, as discovered by Mumtaz & Hopkinson (2010). Scanning the powder bed first with a low energy laser to sinter the powder followed by melting with higher powered laser could also reduce the spattering phenomenon. Commercially, spattering is a major issue hindering the expansion of the powder bed area since the effectiveness of the gas flow is limited in transporting spatter particles over to the outlet. For example, all variants of machines offered SLM Solutions (Lubeck, Germany) have limited powder bed widths of 280 mm (in the general direction of inert gas flow). Therefore, newer innovations should be explored in order to optimise

the spatter removal during SLM.

A recent study involved three methods to remove the spatter in situ during a laser ablation process of aluminium composites Popescu et al. (2016). They include using an argon gas jet and fused silica plates with the former only proving to be efficient for 1 - 2 kW laser pulses. Nevertheless, in terms of the material, bulk metal is used as the workpiece in such laser-based manufacturing and machining processes while material powder is used in SLM.

2.2.4 Monitoring Systems

More recently, a greater number of monitoring systems have emerged in order to capture the SLM process at the micro-scale. Bidare et al. (2017b) created an open-architecture system for powder bed fusion monitoring. Using x-rays, their simple and portable system allowed the in-situ viewing of the process at the powder bed level while also being capable of producing parts with > 99% density of stainless steel 316L parts. In their initial study, they also demonstrated the application of Schlieren imaging which captured the interactions of the laser plume with the shielding gas flow across the powder bed. This concept was later extended to a full investigation in another work where high-speed imaging was also applied to elucidate the effects of laser beam and powder bed interactions (Bidare et al., 2017a). It was in this work that they successfully captured the visualisation of the argon gas flow and its interactions with spatter particles. The developed system was then tested with sub-atmospheric and high pressure atmospheres as elaborated earlier on (Bidare et al., 2018a,b).

High-speed x-ray imaging and diffraction techniques have also been employed to characterise the laser powder bed fusion process (Zhao et al., 2017). High spatial and temporal resolution images of the keyhole pore formation was revealed, among the other melt pool dynamics. The developed system was also capable of tracking the motions of Ti-6Al-4V particles, recording the maximum ejection speed to be as high 15 m/s. Additionally, Leung et al. (2018a) uncovered mechanisms of pore migration by Marangoni driven flow, pore dissolution and dispersion as a result of laser-remelting, by using a similar monitoring system based on x-rays. A prediction model to detect the changes in melt track morphology was also proposed. In a separate study using in-situ and operando synchrotron x-ray real time radiography, Leung et al. (2018b) reported that for stainless steel 316L, which has a low viscosity melt, spatter generation was observed to have diameters up to 250 μm and an average velocity of 0.26 m/s. Finally, with regards to spattering, Guo et al. (2018) reported on the time-scales of the melting, vapour jet/plume formation and argon gas flow formation to be in the micro, tens of micro and lastly hundreds of microseconds respectively. This was done experimentally using an in-situ high-speed high-energy x-ray imaging system. It was also shown that particles in the region be-

hind the laser beam were entrained by the argon gas flow. Environment pressure also played a role in influencing the powder spatter behaviour since at higher pressures, argon gas flow entrainment occurs, leading to an increase in the ejections of hot spatter particles. Hence, it was suggested that pre-sintering of the powder bed, adjusting the layer thickness and also the environment pressure could control the intensity of powder spattering.

Therefore, the monitoring systems that have been proposed would definitely be relevant in improving the removal of spatter particles, under the influence of the inert gas flow as explained in the next subsection of this thesis.

2.2.5 Role of Inert Gas in Build Chamber

Prior to the initialization of the powder bed laser scanning, inert gas (argon, nitrogen or helium) is pumped into the sealed build chamber. For the SLM Solutions machines, argon gas is pumped in from the right to the left side (in the negative x direction). There are two reasons for the introduction of the inert gas; firstly, oxidation of the molten powder needs to be minimised as much as possible. Hence, scanning only starts when oxygen content is below 0.05%. Secondly, during the scanning itself, the flow of gas aids in the removal of unwanted spatter as a result of the ionised metal vapour and plasma plume that exert recoil pressure on the melt pool (Mumtaz & Hopkinson, 2010). Flow uniformity close to the powder bed region is also needed to improve the consistency and uniformity of part properties such as compression strength and density (Ferrar et al., 2012). On the other hand, Zhang et al. (2013b) investigated SLM of pure Ti under vacuum (0.0001 bar in reality) using a self developed SLM machine, which was claimed to remove the gas expansion during scanning of the powder bed. Unfortunately, the observations of spatter under vacuum conditions were not documented. Increasing gas flow speed has also shown to higher density in components (Meiners, 2014). Laser energy could also be wasted on burning the suspended spatter (beam scattering), leading to lower energy input at the powder bed for scanning. As a result, the melting of the powder bed is not effective due to the prior laser-particle interaction.

The effects of the type of inert gas used have also been investigated. Wang et al. (2014) concluded that the type of gas used did not affect the part density or hardness, with a high density of 97 % achieved. However, parts built using helium gas had inferior mechanical properties, which could be attributed to the formation of pore clusters in the microstructure. As compared to conventionally manufactured parts, the SLM parts showed 1.5 times the yield strength, and up to 20 % higher UTS and twice the elongation to failure. Dai & Gu (2015) performed experiments and simulations to study the effect of the gas on metal vaporization behaviour. It was found that when argon gas was used, the melt pool depth reached a stable state due to a uniform recoil pressure as exhibited by

Figure 2.7: Powder accumulation on left side of SLM Solutions 500 HL build chamber

the upwards direction of the evaporated material. Thus, a sound surface morphology is achieved. This is as opposed to the case of nitrogen gas, where humps in the top surface emerged as the vapour tends move towards the front of the laser beam during scanning. Hence, research has shown that the type of gas chosen is critical in the surface finish of the final part. However, in both cases, the direction of gas flow was not specifically stated. This could prove to be a fundamental parameter in the movement and deposition of vapour material, and more importantly, the accumulation of spatter as seen in Fig. 2.7.

In a recent study, it was shown that the spattering behaviour could be controlled by the environment pressure. An increase in the surrounding pressure brought about a decrease in the intensity of spattering, due to the affected divergence angle of the argon gas flow and the vapour jet (Guo et al., 2018).

Much research has been dedicated to investigating the formation and effects of spattering, via both experiments and simulations. However, limited study has been done on characterising spatter ejection in three-dimensions with the use of two high speed cameras Bidare et al. (2017a); Ly et al. (2017). More noticeably, simulations of spatter transport by the gas flow have not yet been performed other than the simulation studies done by Philo et al. (2018) which showed that spatter accumulation on the powder bed decreased by 26.64 % through modifications on the gas inlet design for the Renishaw AM250 machine. Nonetheless, the scanning strategy or laser parameters were not mentioned in their experimental work on SLM of stainless steel 316L.

2.3 Particle-laden Flow

Particle-laden flow refers to the two-phase, gas-particle flow where the continuous or carrier phase is the fluid and the dispersed phase is the solid. This phenomenon is commonly observed in the chemical, agricultural, mining and pharmaceutical sectors. To

understand how particles are carried by the flow for the effectiveness of particle transport, much effort has been made in modelling the process using CFD to minimise time and costs (Curtis & van Wachem, 2004; Elghobashi, 1994). However, to the best of the author's knowledge, no study has been made with regards to spatter removal by gas flow in SLM.

The fluid dynamics can be approached from the Lagrangian or Eulerian method. In the Lagrangian method, the dynamics are understood from the viewpoint of fixed particles as they move through space and time, analogous to sitting in a boat and drifting down a river. Hence the motion and path of individual particles can be derived. On the other hand, the Eulerian approach is where the dynamics are observed from a fixed point in space, similar to sitting at the bank of a river and watching water pass the fixed location (Grushka & Grinberg, 2016). The fluid and particle phases are treated as moving and interacting continua. Some of the characteristics of the particle-laden flow that are considered include particle-particle interactions, solid volume fractions variations and also particle velocity fluctuations. These effects are undoubtedly influenced by the properties of the particle such as shape, size, density and also the concentration. Effects of flow properties such as pressure, velocity, viscosity, temperature and compressibility have also been studied. Additionally, the turbulence level of the flow as categorised by the Reynolds number shown below, plays a critical role, with the formation of eddy and vortical structures.

$$Re = \frac{\rho V L}{\mu}$$

where ρ is the fluid density, V is the fluid velocity, L is the characteristic length and μ is the dynamic viscosity. The Reynolds number is a dimensionless quantity defined as the ratio of inertial to viscous forces.

As a result of the particle-flow interactions and particle-particle collisions, particle clustering is often observed where the particles agglomerate and break up constantly, typically when the solids volume fraction exceed 1%. Such preferential concentration of particles by turbulence have also shown to occur in different flows such as wall-bounded flows, plane and axisymmetric flows and complex shear flows (Eaton & Fessler, 1994). Therefore, the right modelling method has to be adopted to account for the clustering effect. This is generally done using Discrete Element Method (DEM) which models the interaction between individual particles (Takeuchi et al., 2008). However, at low mass loadings, inter-particle collisions cannot be ignored for the development of particle concentration profiles in horizontal channels (Sommerfeld, 2003).

The effects of the geometrical set up have also been studied. For example, for particle-laden flow in turbulent square ducts, Zhang et al. (2015b) showed that gravity, collisions and secondary flow effects determine the distribution of different sized particles. $50\text{ }\mu\text{m}$

particles tend to deposit near the side walls due to the secondary flow effects. However, particles between 100 and 500 μm are mostly found near the center of the floor of the duct, as greatly influenced by gravity and inter-particle collision effects. Numerical calculations using Lagrangian models performed by Sommerfeld (2003) showed that increasing wall roughness reduces the average transport velocity of particles while increasing the fluctuating energy. Increasing the wall height also reduces the frequency of wall collisions and thus smaller particles are better dispersed by turbulence.

With regards to the spatter removal in SLM, the two processes described below are mainly observed.

Sedimentation the process where particles initially suspended in fluid flow settles and eventually gets deposited on the floor of the domain as a result of the available forces acting on them such as gravity, centripetal force or electromagnetism.

Saltation where the settling particles fall out of the flow and collide with the particle bed, inducing kinetic energy and lift to the initially static particles, causing a "chain reaction" when gravity pulls down the suspended particles thereby disrupting the uniformity of the bed.

For this study, the Stokes number, a dimensionless number which characterises suspended particle behaviour in fluid is of main interest. It is defined as the ratio of the characteristic particle time to that of the flow:

$$St = \frac{2}{9} \frac{\rho_p r_p^2 U}{\mu_f L_o}$$

where ρ_p is the particle density, r_p is the particle radius, μ_f is the fluid dynamic viscosity and L_o is the characteristic length. As a guideline, the for $St \ll 1$, the particle follows fluid streamlines, in other words, perfect advection. Otherwise, for $St > 1$, the particle is dominated by inertia and continues along its initial trajectory.

A wide range of studies have been performed, where the use of CFD simulations together with the Lagrangian approach across the micro to meso and then to macro scales, as reviewed by Tenneti & Subramaniam (2014). For example, Akilli et al. (2001) investigated the characteristics of particle flow in a horizontal pipe after a 90° elbow. The CFD simulations coupled with the Lagrangian method for the particles while accounting for particle-particle and particle-wall collisions, showed good agreement with the particle size distribution observed in the experiments. To increase the efficiency of the Lagrangian method, Kloss et al. (2009) proposed a technique to switch from Discrete Element Method (DEM), where particle-particle collisions are computed, to DPM in dilute regions of the fluid domain. Their method showed that there were no significant effects on the final results of the simulation.

More recently, Philo et al. (2018) performed Eulerian-Lagrangian simulations in ANSYS Fluent using the Discrete Phase Model (DPM) which was validated with hot-wire anemometry data of the inert gas flow velocities. Identification of recirculation zones and characterisation of spatter accumulation showed how undesirable particles get deposited within the SLM chamber. Ladewig et al. (2016) reported re-depositions of process by-products in regions of low flow velocity near the gas outlet of the SLM chamber. However, the validation of the mentioned work in terms of spatter distribution on the powder bed is yet to be carried out.

2.4 Summary

To summarise, literature review has revealed the negative effects of spatter particles on the powder bed which include its protrusion into the upper layers and requiring more energy to completely melt. Their specific morphology and ejection characteristics were also reported. However, with the introduction of the inert gas flow in commercial systems, possible interactions of these spatter particles and the laser beam, under the influence of the gas flow, could affect the properties of the printed parts. In other words, while other researchers studied the ejection trends and contamination effects on the powder bed, this PhD seeks to investigate the laser-spatter-gas interactions which could possibly take place above the powder bed. Following this, the distribution characteristics of the spatter particles on the powder bed as a result of their transport by the inert gas flow has not been reported prior to the studies undertaken during this PhD. This includes both experimental and simulation studies.

Chapter 3

Effects of laser-spatter-gas interactions on UTS of printed parts

In this chapter, the effects of possible laser-spatter-gas interactions on the Ultimate Tensile Strength (UTS) of printed parts were investigated. The results showed that regardless of part placement and flow velocity, scanning against the flow always leads to higher part strength. Part of this work on the accumulation of spatter was published in the 2nd International Conference on Progress in Additive Manufacturing, 2016. The full work in this chapter has been published in **Anwar, A. B., & Pham, Q.-C. (2017). Selective laser melting of AlSi10Mg: Effects of scan direction, part placement and inert gas flow velocity on tensile strength. *Journal of Materials Processing Technology*, 240, 388-396.**

3.1 Introduction

In SLM, the removal of spatter from the powder bed is critical in ensuring a good build quality of the printed parts. This is done by the inert gas flow, which is blown from one side of the chamber to the outlet, transporting the spattered powder away from the powder bed. During this process, laser-particle-gas interactions occur, whereby their effects have not been largely studied. Therefore, investigation into the effects of such interactions was performed by varying three factors: part placement within the chamber, inert gas flow velocity and laser scan direction, either in the same or opposite to the direction of gas flow. The experiments were carried out using the SLM Solutions 280 HL machine and a 2^k ($k = 3$) factorial design as part of the Analysis of Variance (ANOVA) method. The main effect studied was the Ultimate Tensile Strength (UTS) of the printed parts, an indicator of the build quality. The powder spattered during laser scanning was also investigated, as it plays an important role in the process and, ultimately, on part quality. In particular, the quantity and the composition of the powder deposited near the outlet (after it was blown away from the powder bed by the gas flow) was measured,

as it might reflect the amount of spatter generated and evacuated by the process. A high-speed camera was also used to capture the process near the scanning site in order to gain insight into the laser-spatter interactions.

3.2 Materials & Method

3.2.1 SLM Parameters

A SLM Solutions 280 HL machine equipped with a twin (2×400 W) CW Ytterbium fibre laser was used in the experiments. The build chamber of the machine has dimensions $430 \times 368 \times 383$ mm (the y dimension *i.e.* the length of the chamber here being the full distance covered by the recoater) and the build area has dimensions 280×280 mm. Prior to the experiments, the build chamber was flooded with argon gas to reduce the oxygen level to less than 0.1%, and the flow was maintained throughout the experiment. The gas was blown from the right side of the build chamber towards the left, see Fig. 3.2. The build platform was pre-set to a temperature of 150°C before laser initialization. Other parameters set in the SLM Build Processor include: laser power of 350 W, layer thickness of $100\text{ }\mu\text{m}$, laser speed of 900 mm/s and hatch space of 0.12 mm.

Spherical AlSi10Mg which had been gas atomised with nitrogen was used as printing powder. The particle size distribution is 20 - $63\text{ }\mu\text{m}$, while the chemical composition is listed in Table 4.1. For this study, rectangular cross sections with a dimension of 110×16 mm were scanned on the powder bed. The chemical composition was obtained from the powder supplier, SLM Solutions.

Table 3.1: Chemical composition (weight %) of AlSi10Mg

Element	Minimum	Maximum
Al	Balance	Balance
Si	9.000	11.000
Fe	0.250	0.450
Mg	-	0.400
Cu	-	0.050
Zn	-	0.100
Ti	-	0.150
Mn	-	0.005
Ni	-	0.050

3.2.2 Protocol

For this study, the independent variables “scan direction”, “part location” and “gas velocity” were chosen to investigate how the possible laser-particle-gas interactions during

SLM would affect the UTS of the printed parts, see Table 3.2.

Table 3.2: 2^3 design experiment

Factor	Low(-)	High(+)
A: Scan Direction	$-x$	$+x$
B: Part Location	left	right
C: Gas Velocity	30%	60%

Scan direction Since the argon gas is pumped into the chamber from the right inlet to the left outlet, the scan vectors were set to align in the x direction as in Fig. 3.1. In this way, the scan direction was either in the direction to the gas flow ($-x$) or opposite to it ($+x$).

Part location The parts were placed either on the left or on the right side of the build platform, and equally spaced apart, as in Fig. 3.2.

Gas velocity Gas velocity was either 30% or 60% of the maximum gas velocity, as set in the pre-processing software in the Machine Control System (MCS). The values at 30% and 60% of maximum gas velocity were found to be approximately 1.43 and 2.87 m/s.

Figure 3.1: Local scanning strategy for inner regions in (a) $-x$ (b) $+x$ directions

Figure 3.2: Layout of part placement

The 2^3 factorial design implied 8 experimental conditions, see Table 3.3. For each condition, one run was conducted in which three parts were printed. Prior to each run, the build chamber including the laser lens surface was cleaned and a new build plate which had been sand-blasted was put in place. Fresh powder which had been sieved was used throughout the experiment.

Table 3.3: Plus and Minus table for 2^3 design experiment

Run	Factor						
	A	B	C	AB	BC	AC	ABC
1	-	-	-	+	+	+	-
a	+	-	-	-	+	-	+
b	-	+	-	-	-	+	+
ab	+	+	-	+	-	-	-
c	-	-	+	+	-	-	+
ac	+	-	+	-	-	+	-
bc	-	+	+	-	+	-	-
abc	+	+	+	+	+	+	+

3.2.3 Analysis of the printed parts

The printed parts were machined according to ASTM E8 Specimen 3 standards (see Fig. 3.3), and subjected to tensile strength tests using the Instron 5569 tensile tester. A 50kN load was used along with a strain rate of 0.25 mm/mm/min.

Figure 3.3: Sample of machined tensile specimen

The chosen fracture sites were then coated with a thin layer of gold and analysed for their elemental composition using the Field Emission Scanning Electron Microscope (FESEM), JOEL 7600F.

3.2.4 Spatter

The powder that was deposited near the outlet (more precisely, in the yellow-marked region (254×48 mm) in Fig. 3.2) was collected using a scoop after scanning every 10 layers, resulting in 15 samples being collected for each run.

The mass of the samples was measured and SEM and EDS analyses were performed on sampled individual spatter particles from runs *c* and *ac*. The SEM-EDS analysis makes use of electrons in a vacuum environment to capture high magnification images and conduct non-destructive elemental testing on the samples.

The reasons why we chose to collect the spatter at that area are: (i) it is not possible to collect the spatter directly on the powder bed as it is mixed with fresh powder; (ii) it is not possible either to collect the powder blown out of the outlet, as one cannot completely clean the powder collector (gas filter) between runs; (iii) on the contrary, the region near the outlet where the powder is collected in our experience could be cleaned up several times per run, resulting in reliable results; (iv) finally, it can be safely assumed that the quantity of the powder collected near the outlet is proportional to the total quantity blown out of the powder bed and that its composition is similar.

3.2.5 High-speed camera observation

To observe the spattering process and laser-particle-gas interactions closely, video footage for runs *c* and *ac* were captured using the Phantom Miro®eX4 high speed camera with the Nikkor 50 mm f/1.8D lens at 1200 fps and a resolution of 800×600 as in Fig. 3.4.

Image processing was performed using Python and Open Source Computer Vision (OpenCV). Otsu's method for thresholding was then applied to the extracted images to quantify any difference between the two runs (Otsu, 1979).

Figure 3.4: Camera set-up placed outside SLM Solutions 280 HL build chamber observation window (computer not seen in image)

3.2.6 Statistical analysis

A simple ANOVA test was then conducted to observe the effects of the variables on UTS and the amount of spatter collected. The null hypothesis (H_0) being that the mean is the same for all the runs (the factor has no effect on the response) while the alternative hypothesis (H_1) is that the mean is different (factor has effect on the response). It is important to note that since the effect of the scan direction on the parts' tensile strength is to be tested, randomisation of the runs for the collection of spatter samples was not carried out so that parts with the same run parameters could be obtained. The 2-level factors and their interactions are tabulated in Table 3.3.

Regarding the tensile strength test, there were 8 runs and 3 specimens per run, resulting in 24 samples. For each run, the average and standard deviation of the UTS were computed across the 3 samples. Next, a 2^3 ANOVA analysis was conducted to assess the effects of the three independent variables on the UTS.

Regarding the quantity of spatter collected near the outlet, there were 8 runs and 15 samples collected per run, resulting in 120 samples. For each run, the average and standard deviation of the mass of the samples were computed across the 15 samples. Next, a 2^3 ANOVA analysis was conducted to assess the effects of the three independent variables on the quantity of collected spatter.

All statistical calculations were done using the Minitab software.

3.3 Results

3.3.1 Tensile strength

The average and standard deviation of the UTS for each run are shown in Fig. 3.5A. The parts with the averaged lowest (246.29 MPa) and highest (330.976 MPa) UTS came from run *b* and *abc* respectively. At the lower velocity, it can be seen from runs *1*, *a*, *b* and *ab*, that for both left and right placement of the parts, scanning against the flow led to significantly higher UTS since the error bars do not overlap.

Figure 3.5: **A:** Mean UTS (MPa) and $\pm$ standard deviation in each run. **B:** Main effects plot for UTS (MPa).

A large number of pores were seen on all the machined specimens.

Initial tests on the residuals of the data on UTS were performed. It was found that the distribution is slightly asymmetrical with a negative skew and kurtosis value of -0.41 and -0.69 respectively as seen in the histogram in Fig. 3.9. The residual points are also close to a straight line, showing that the residual distribution is close to normal. Independent distribution from the observation order plot and constant variance from the fitted value plot are also satisfied. Therefore, the residual analysis has been performed and the assumptions for ANOVA have been satisfied, deeming the following ANOVA results reliable.

The effects of the main factors are illustrated in Fig. 3.5B. It can be observed again that (i) higher gas velocity and (ii) scanning against the gas flow led to higher UTS, while the effect of part placement on UTS was weaker.

To further verify the effects of the factors on the UTS of the parts, a Type I error probability $\alpha = 0.01$ was adopted for the ANOVA test, see Table 3.4. For main factors *A* and *C*, $F_0 > F_{0.01,1,16}$ at a value of 8.531, as tabulated in Table 3.4. Therefore both scan direction and gas velocity have a significant effect on the UTS of the printed parts. However, the part placement and higher order interactions do not influence the part

Figure 3.6: Residual plots for UTS

strength significantly.

Table 3.4: ANOVA for the 2^3 design experiment (UTS)

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	P-value
<i>A</i>	4208.9300	1	4208.9300	12.9645	0.00240
<i>B</i>	30.4410	1	30.4500	0.0938	0.76335
<i>C</i>	10111.9245	1	10111.9245	31.1472	0.00004
<i>AB</i>	1215.4996	1	1215.4996	3.7440	0.07088
<i>AC</i>	1729.6728	1	1729.6728	5.3278	0.69717
<i>BC</i>	50.9906	1	50.9906	0.1571	0.03468
<i>ABC</i>	30.7634	1	30.7634	0.0948	0.76226
Error	5194.3885	16	324.6493		
Total	22572.6195	23			

3.3.2 Composition of spatter

The presence of oxygen was detected and found to be close to 20% weight percentage for each run. Also the Al and Si contents reduced as a result of possible oxidation effects. However, for the same magnification (90x), the spatter can be seen to be significantly larger in size, at least twice that of the fresh powder.

Additionally, the SEM images fracture sites of tensile specimens from runs *abc* and *b* were compared as they had the highest and lowest UTS respectively, see Fig. 3.8. It can be observed that more pores and unmelted powder were seen for run *b* in Fig. 3.8B.

Figure 3.7: SEM images of **A**: Fresh powder; **B**: spatter collected near the outlet observed; **C**: Single particle of spatter. **D**: Sample EDS result of single spatter.

Table 3.5: Chemical composition (weight %) breakdown obtained from a single powder particle

Element	Fresh Powder	Run <i>c</i>	Run <i>ac</i>
Al	82.1	69.18	69.69
O	-	17.51	18.39
Si	17.27	12.19	11.63
Mg	0.63	1.12	0.29

Figure 3.8: SEM of fracture sites. **A:** A sample from run *abc*. **B:** A sample from run *b*. One could observe a with higher porosity (circled) and unmelted powder (arrow) in this run compared to run *abc*.

3.3.3 Quantity of spatter collected near the outlet

Initial tests on the residuals of the data on spatter mass were performed. It was found that the distribution is slightly asymmetrical with a positive skew value of 0.10 and a negative kurtosis of -1.13 as seen in the histogram in Fig. 3.9. Variance heterogeneity and doubt with respect to the normal distribution of the residuals were identified from the graphs in Fig. 3.9. However, ANOVA was still performed due to its robustness in testing hypotheses about means, instead of the non-parametric Kruskal-Wallis test (Feir-Walsh & Toothaker, 1974).

Figure 3.9: Residual plots for mass of accumulated spatter

From Fig. 3.10A, the largest quantity of spattered powder occurred for run *ac* where

the parts were scanned against the gas flow at 60% of the maximum velocity and placed on the left side (run *ac*). On the other side of the spectrum, the smallest quantity of spatter took place for the opposite configuration at run *b*.

Figure 3.10: **A:** Mean mass of collected powder (g) and $\pm$ standard deviation in each run. **B:** Main effects plot for mass of collected powder (g)

The effects plot in Fig. 3.10B show that (i) scanning against the gas flow, (ii) placing part on the left side of the powder bed (further from the gas inlet and closer to the outlet), and (iii) higher gas velocity led to larger amount of collected powder.

The ANOVA results for the quantity of collected spatter are tabulated in table 3.6. Also using $\alpha = 0.01$, all variables, including their interactions (except the highest interaction) have a very significant effect on the amount of accumulated spatter since $F_0 > F_{0.01,1,112}$ at a value of 6.8667.

Table 3.6: ANOVA for the 2^3 design experiment (spatter)

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	P-value
<i>A</i>	4.0095	1	4.0095	354.7643	<0.00001
<i>B</i>	10.0120	1	10.0120	885.8797	<0.00001
<i>C</i>	55.0593	1	55.0593	4871.7477	<0.00001
<i>AB</i>	1.6130	1	1.6130	142.7214	<0.00001
<i>AC</i>	0.1389	1	0.1389	12.2898	0.00067
<i>BC</i>	0.1467	1	0.1467	12.9771	0.00047
<i>ABC</i>	0.0041	1	0.0041	0.3613	0.549
Error	1.2658	112	0.0113		
Total	72.2493	119			

3.3.4 Visual observation of laser-spatter-gas interactions

To study the laser-spatter-gas interactions more closely, six snapshots of the scanning along a single scan vector at equal intervals were extracted from the video recordings. It can be observed that much more spattering is present in the form of sparks as in

Fig. 3.11A from t_2 to t_4 . At t_4 , a significantly large spark was also captured. The ejection angle is also much less apparent and defined as the spattering occurs generally upwards and sideways. However, when scanning against the flow, the angle at which the spatter is ejected generally decreases from the start to the end of each scan vector (110 mm). As an example, for run *ac* in Fig. 3.11b, the initial ejection angle was recorded to be 26.6° and decreased to approximately 8.75° towards the end of the scan vector. This shows the effect of the gas flow on the melt ejection characteristics, how the ejection angle decreases with the strength of the gas flow.

3.4 Discussion

Based on the results obtained and existing literature, we now argue that the two following factors significantly affect the quality of the built part: (i) gas flow velocity and, (ii) direction of laser scan with respect to gas flow.

3.4.1 Effect of gas flow velocity on part quality

The results in Section 3.3.1 showed that the higher the gas flow velocity, the better the part quality. This effect is most likely mediated by the spatter: gas with higher velocity can carry more spatter to the outlet, leaving less spatter on the powder bed, which in turn results in better part quality. Section 3.3.3 showed that higher gas velocity indeed implied significantly more powder deposited near the outlet, contributing less to the contamination of the powder bed. However, although higher gas velocity improves part quality, increasing gas velocity too much would lead to the transport of fresh powder from the powder bed. Consequently, the layer thickness uniformity would be disrupted. Therefore, there will be an optimal gas velocity that realizes the best compromise between the removal of spatter and maintaining the fresh powder on the powder bed.

Next, little has been reported regarding the effect of spatter during the SLM of fresh powder on part quality. An example would be that tensile parts manufactured by contaminated powder had lower UTS as compared to those printed by fresh powder, as a result of more inclusions (Liu et al., 2015). Hence, it can be safely posited that the more spattered (non-fresh) powder is mixed to the fresh powder on the powder bed, the lesser the part quality. Fig 3.8B gives a possible explanation: the existence of non-fresh powder results in larger pores in the part, which in turn might act as crack initiation sites during the tensile tests, which would account for the lower UTS. Section 3.3.2 showed through SEM analyses that the spatter has indeed a different composition from the fresh powder. The presence of oxide layers on the surface accounts for the difference in size, which confirms the results on the presence of inclusions due to the spatter reported by Liu et al. (2015). To validate the difference in porosity as in Fig. 3.8, the density of the

Figure 3.11: Images extracted from video at intervals of $24 \mu\text{s}$. (a) Run *c* (b) Run *ac*.

parts from runs *abc* and *b* were measured to be $2.661 \pm 0.077 \text{ g/cm}^3$ and $2.528 \pm 0.001 \text{ g/cm}^3$ by using the Archimedes' principle with ethanol as the auxiliary liquid.

3.4.2 Effect of scan direction on part quality

Scan direction with respect to the flow was also found to significantly affect part quality (Section 3.3.1), which is more unexpected. To explain this relationship, the ejection of the molten material during laser scanning with respect to the gas flow is first addressed.

The spattering patterns in SLM could be similar to that found in laser welding (Fabbro, 2013). A study done on the spatter formation mechanism during high power laser welding of pure titanium showed that at high welding speeds of 300 mm/s, the motion of plumes to the upper-rear region of the keyhole induced "spattering of the melt behind the keyhole inlet in the molten pool" (Nakamura et al., 2015). Therefore, a similar phenomenon could have occurred during the experiment at a high scan speed of 900 mm/s, where the motion of the vapour plume exerts pressure on the melt pool, causing oscillations to be generated inside the melt pool and possibly producing spatters on the rear of the melt pool rim, in the opposite direction to that of the laser beam scanning as seen in Fig. 3.12.

During laser scanning, when the gas flow carries the spatter to the outlet, a fraction of the spatter could be blown into the laser beam path and disintegrate into finer particles. These particles were visually observed to be more prevalent when scanning in the direction of the gas flow, as opposed to scanning against. However, they were not recorded since it was not possible to capture the smoke trails with our camera due to their fine nature and chaotic movement in the turbulent gas flow which circulated upwards towards the ceiling of the chamber.

When scanning in the direction of the flow (Fig. 3.12a), the spatter is more likely to be blown into the path of the beam as compared to scanning against the flow (Fig. 3.12b), because of the location of melt ejection with respect to the movement of the laser beam. The results in Section 3.3.3 lend support to this experiment, as scanning in the direction of the flow was associated with significantly less powder collected near the outlet (hence, possibly more spatter burnt by the laser). This finding is further reinforced by the snapshots in Fig. 3.11: scanning in the direction of the flow was associated with larger "sparks" above the powder bed, which in turn hint at more spatter burnt by the laser beam. To further validate the difference in the amount of sparks produced, image processing of the snapshots in Fig. 3.11 were performed. The regions of interest where the sparks are observed, were cropped off the original images and analysed by first converting them to grayscale. Thresholding was then imposed to convert the grayscale images to their binary form, where the pixels are either 0 or 255 in value. This was done by calculating the threshold value using Otsu's method which separates the two peaks in

the grayscale histogram of the images. All pixel intensities lower than the threshold value were set to 0, while those above the threshold were set to 255 (Rosebrock, 2016). Every cropped snapshot gave a resolution of 142×800 . To quantify the difference in the amount of sparks generated, the 0 value pixels which represented the sparks were calculated for each snapshot. When scanning with and against the flow, the mean number of 0 value pixels detected were 69.8 ± 40.9 and 42.2 ± 8.9 respectively. Therefore, this shows that more sparks were observed when scanning in the gas flow direction.

Figure 3.12: Schematic of laser beam scanning (a) in and (b) against the direction of the gas flow which might have caused the spatter in the latter case

Next, as scanning in the direction of the flow generates more burning of the spatter, the laser power that effectively reaches the scan site is decreased, resulting in lower UTS. The relationship between laser power and part quality is well documented elsewhere in the literature (Buchbinder et al., 2011; Nishiyama, 2012).

3.4.3 Spatter Accumulation

As established, scanning against the flow and at higher gas velocity, led to both higher UTS and accumulated spatter. To show the relationship between these two outcomes, the results were normalised and compared on the same plot. From Fig. 3.13, it can be seen that generally, the two lines follow the same trend throughout the runs, except for the case of run *ac*, where the ratio increased for spatter but decreased for UTS, coming from run *c*.

Figure 3.13: Normalised column graph for spatter accumulation outside of powder bed and UTS

In general, as more spatter accumulates near the outlet, less of it get deposited on the fresh powder bed, serving as an indication of the amount of contamination which affects the part quality.

3.4.4 Other parameters that can influence part quality

Post processing such as solution heat treatment could be performed to improve the part quality by micro-structural refinement. However, as investigated by Li et al. (2015), despite an increase in ductility, the UTS of another Al-Si alloy (AL-12Si) decreased from 350 MPa to 190 MPa when subjected to solution treatment time to 30 minutes. This was due to the reduction in solid solution strengthening when the trapped nano-sized and spherical Si in the Al matrix precipitated to the grain boundaries.

Other contributors to the spattering are the energy density (Ψ) factors in SLM which include the laser power (P), scan velocity (v), hatch space (h) and layer thickness (t), related by the equation $\Psi = P/v \cdot h \cdot t$ which could possibly impact the formation of metal vapour and plasma plumes (Read et al., 2015; Spierings et al., 2014). Increasing energy transferred to the powder bed could directly result in greater recoil pressure and thus induce more spattering.

Additionally, the beam diameter, number of lasers used, powder material, chamber pressure, platform temperature, scanning patterns and other types of inert gas such as nitrogen are also some variables which could produce different spattering trends (laser-spatter-gas interactions) inside the chamber and subsequently influence the part quality. Thus, more research needs to be performed on the spattering phenomenon and the role of the gas flow in order to minimize its effects during SLM.

3.5 Conclusion

Spattering in SLM is an unavoidable phenomenon which affects the printed part properties. In this study, it was concluded using ANOVA that scanning against the gas flow (+x direction), increasing the inert gas velocity (60%) and scanning close to the outlet (on the left side) leads to higher UTS of the printed parts. Scanning in the direction of the flow significantly reduces the accumulation of spatter on the build chamber base, regardless of the gas velocity and part placement. It was observed that scanning in this direction generally produced more finer particles as the spatter was observed to burn and disintegrate after being carried into the laser beam path. This could have accounted for the significantly lower accumulation and also heat energy loss, leading to incomplete melting of the powder and consequently lower UTS of the parts. While a number of arguments were offered to explain these effects, more work such as using other measurement instruments and/or numerical simulations are still required to understand the highlighted phenomena in detail. Yet, the results obtained here yield practical and easy-to-implement recommendations to improve part quality in SLM processes.

Chapter 4

Spatter distribution on the powder bed

In this chapter, the spatter distribution in terms of mass and size has been characterised. Image processing was also implemented to serve as an immediate assessment tool on the mass distribution. The full work in this chapter has been published in **Anwar, A. B., & Pham, Q.-C. (2018b). Study of the spatter distribution on the powder bed during selective laser melting. *Additive Manufacturing*, 22, 86-97.**

4.1 Introduction

Studies have been made to characterize the deposited spatter on the workpiece in welding and laser drilling. For example, a spatter index was introduced to quantify the spatter in welding using computer vision which was reported to be highly reliable (Bidanda et al., 1989). The authors also concluded that using incandescent light at low angles to the workpiece served as the best arrangement for illumination. Human perception and physical dimension measurements were also employed in the study. Characterisation of the spatter deposition area using image acquisition, processing and analysis was carried out by varying the laser processing parameters in laser percussion drilling (Low et al., 2000b). No quantitative measurements of the amount and dimensions of spatter were performed in the study. An X-ray transmission system was also developed for characterizing spatter in wet welding where the largest spatter was measured at approximately 4.5 mm (Guo et al., 2015). In the case of powder bed fusion processes, a review of the available powder characterisation methods and the effects of varying powder characteristics on part properties was conducted (Slotwinski et al., 2014; Sutton et al., 2017). The techniques include sieve analysis, microscopy (to obtain high resolution images) and also laser diffraction, each with their own pros and cons. However, their work evaluated the fresh powder used for part fabrication and notably excluded any investigations

on spatter and other by products. Spatter distribution on the workpiece was also not investigated.

Regarding the image processing of powder, limited research has been performed on material powder commonly used in Additive Manufacturing (AM). Most recently, image texturing using the bag of visual words computer vision method could supplement existing powder characterisation techniques for AM (Decost & Holm, 2017). Their research only accounted for the fresh powder feedstock in AM and not specifically spatter-contaminated powder. In another study, an in-situ analysis of spatter as a process signature driver was employed to indicate under or over-melting conditions during SLM (Repossini et al., 2017). In other applications, pharmaceutical powder was analysed using a multivariate gray image analysis and it was found that the results were comparable to that using near-infrared spectroscopy (Realpe & Velázquez, 2003). Subsequently, implementation of an algorithm based on the invariant image moments was used to characterise pharmaceutical powder according to morphology and size, despite contact between the particles (Realpe & Velázquez, 2006). Powder particle size was also measured with digital image processing, specifically Matlab (Wu & Yu, 2012). However, the images were taken using SEM, which while useful when obtaining the particles sizes, it is impractical if one intends to investigate the in-situ spatter distribution on the powder bed immediately.

4.2 Materials and Methods

As mentioned earlier, three types of spatter had been reported (Wang et al., 2017). Since droplet spatter generally gets ejected from the rear of the melt pool when laser scanning at higher speeds, maximum amount of spatter would get deposited on the powder bed by the gas flow when scanning against it. Therefore, in this work, unidirectional scanning was adopted in the $+x$ direction to allow more spatter to be collected for quantification purposes.

In order to evaluate the effectiveness of the gas flow in transporting the spatter away from the laser-scanned regions to the chamber outlet, only the gas flow velocity is varied, which is controlled by the gas pump setting prior to the build job initialisation. It was set to 60 and 67 %, which are the lower and upper limits of the range for gas pump setting as indicated in the SLM 280 HL machine user manual. The main reason is that should the pump setting be lower than 60 %, spatter will not be effectively removed from the powder bed, leading to undesired contamination and possible protrusion into the following powder layer. On the other hand, when the pump setting is greater than 67 %, there would be a high possibility of fresh powder getting picked up by the gas flow. Consequently, the powder layer uniformity would be disrupted and inter-layer bonding would be weakened.

4.2.1 SLM Parameters

The SLM Solutions 280 HL (SLM Solutions Group AG, Lübeck, Germany) machine equipped with a twin (2×400 W) CW Ytterbium fibre laser was used in the experiments. The power bed has a dimension 280×280 mm. The laser beams had a focal point diameter of approximately $80 \mu\text{m}$. Prior to the experiments, the build chamber was flooded with argon gas to reduce the oxygen level to less than 0.1%, and the flow was maintained throughout the experiment. The gas was blown from the right side of the build chamber towards the left. The build platform was pre-set to a temperature of 150°C before laser initialization. Other parameters set in the SLM Build Processor include: laser power of 350 W, layer thickness of $100 \mu\text{m}$, laser speed of 900 mm/s and hatch space of 0.12 mm.

Spherical AlSi10Mg which had been gas atomised with nitrogen was used as printing powder. A Scanning Electron Microscope (SEM) image of the fresh powder is seen in Fig. 4.1. The particle size distribution is $20 - 63 \mu\text{m}$, while the chemical composition is listed in Table 4.1. The chemical composition was obtained from the powder supplier, SLM Solutions.

Figure 4.1: SEM image of fresh AlSi10Mg powder

Table 4.1: Chemical composition (weight %) of AlSi10Mg

Element	Minimum	Maximum
Al	Balance	Balance
Si	9.000	11.000
Fe	0.250	0.450
Mg	-	0.400
Cu	-	0.050
Zn	-	0.100
Ti	-	0.150
Mn	-	0.005
Ni	-	0.050

4.2.2 Gas Flow

Gas flow velocity was measured using hot wire anemometry for accurate readings with good spatial resolution and high frequency response. Measurement points were selected to be at 3 points regularly spaced apart, for both the top and bottom gas inlet. The measurements only started when the gas pump was allowed to be switched on, i.e. when the oxygen level inside the chamber was below 2%.

At 60 and 67 % of maximum gas pump input, the recorded velocity was at 1.41 ± 0.24 m/s and 1.57 ± 0.21 m/s at the bottom gas rail inlet respectively. It should be noted that the actual gas velocity at the inlets fluctuate according to the condition of the gas filter. Overtime, for the same gas pump setting, the actual velocity output decreases due to waste build up at the filter since the argon gas is recirculated back into the chamber by the pump. Therefore, the experiment sets were conducted continuously to ensure that the filter status was relatively maintained at 43.5 ± 0.3 mbar during the SLM process.

4.2.3 Experiment protocol

To study the spatter distribution closely, the powder bed was segmented into equal sized columns of 40×120 mm as seen in Fig. 4.2. Images of the powder bed directly after laser scanning was performed first, in order to obtain an initial overview of the untouched powder bed and possible disruptions caused by the motion of the recoater. Characterisation of the spatter distribution on the powder bed was done by mass measurement and then size determination. The spatter was collected after 20 laser-scanned layers to ensure sufficient spatter was available for analysis. The experiment was repeated four times at 60 and 67% gas pump settings, giving a total of eight data sets.

Figure 4.2: Layout of scanning region of 80×40 mm, with spatter on powder bed distributed on equal columns of 40×120 mm each. Red arrows indicate unidirectional laser scan vectors while green arrows represent inert gas flow. The scanning order was set from the top going downwards (-y direction)

Image processing

The objective is to implement a simple yet effective method of acquiring the images for analysis. Top-down images were taken using a Sony alpha a6000 camera, which has a maximum resolution of 6000×4000 pixels, mounted on an aluminium frame as seen in the set-up in Fig. 4.3 and subsequently processed using the image processing software, ImageJ. The calibration factor was determined to be 15.9 pix/mm. Lighting was provided by the built-in LED lights which lined the ceiling of the chamber closer to the front door.

Figure 4.3: Image capturing set-up

To maintain consistency of the images captured, four circular neon coloured markers at 8 mm in diameter were placed outside the substrate, on the base of the chamber. The pixel coordinates of the center of each circle were determined to be used as reference points. Perspective transformation was then carried out followed by acquiring the difference between the before and after laser scanned images.

From the findings of previous studies, the sizes of spatter exceed the layer thickness used in the current study (i.e. larger than $100\text{ }\mu\text{m}$) (Anwar & Pham, 2017; Simonelli et al., 2015). Therefore, spatter deposited on the current layer could protrude into the subsequent layer above. However, pressure exerted during the laying of the powder by the recoater could also depress the spatter downwards, minimising any spatter protrusion.

To quantify the observed spatter, comparisons between before and after images of the laser scanned powder bed for the third to tenth layers were made, giving a total of nine pairs of images. It is important to note that since the first layer of powder is coated manually and verified by the naked eye, it is deemed not suitable for analysis due to the inevitable associated inconsistencies. Also to account for the possible unevenness of the substrate surface due to previous warpage and distortion, the third layer was identified to be suitable as the initial layer. The Renyi entropy threshold method was deemed suitable for the purpose of this study. For this method, the image was analysed globally such that a threshold was chosen from the gray level histogram based on the entropy concept derived from information theory (Kapur et al., 1985).

From visual inspection of the powder bed with the naked eye, spatter particles are easily distinguishable from the fresh powder due to their darker contrast. This is reflected in the images taken using the camera. Therefore, the object of interest is distinct

from the background, deeming it feasible for the image to be segmented into an object and a background. Such bilevel thresholding results in the gray level image to be bimodal. Subsequently, the selected threshold chosen corresponds to the valley of the gray level histogram. Pixels on either side of the threshold would be assigned to the background or object accordingly (Sahoo et al., 1997).

Spatter percentage or "SP" is then used as the term to report the quantity of pixels which approximately represents the spatter is then reported as a fraction of the individual columns (424×1272 pixels each).

Mass measurement

The spatter together with the fresh powder in the respective cells was collected using a handheld suction based powder collection device (BioTX Automation Inc., Livingston, Texas, U.S.A) and a regular scoop. They were then sieved one batch at a time using a mechanical shaker by Ro-Tap ® Sieve Shakers (W.S. Tyler, Ohio, USA) and a 12 inch diameter sieve with $63\ \mu\text{m}$ openings as per ASTM E-11 standard. As mentioned earlier, the fresh powder used had a maximum diameter of $63\ \mu\text{m}$. From observations, the spatter particles that were sieved out appeared darker in contrast to the fresh powder and this was the case after sieving was completed.

Size analysis

Static image analysis was used to measure the sizes of the spatter. Therefore, the minimum size is expected to be greater than $63\ \mu\text{m}$. ImageJ software, which is an open source image processing program usually used for analysing scientific complex images, was then used to obtain the spatter diameter from the magnified images taken via optical microscopy. The spatter diameter was then reported in terms of their mean values as indicated in the standard guide for powder particle size analysis (ASTM E2651-13, Section 18.4).

Samples of collected spatter was then analysed using SEM which makes use of electrons in a vacuum environment to capture high magnification images and conduct non-destructive elemental testing on the samples. A thin layer of platinum was coated onto the spatter and the SEM images and the corresponding chemical composition was obtained using the Schottky Field Emission SEM, JSM-5600 machine (JEOL Ltd., Tokyo, Japan).

4.3 Results

4.3.1 Image processing

The typical images captured that were processed are as shown in Fig. 4.4. Renyi entropy thresholding method was then applied, where a dark background and white foreground which approximately represented the spatter was achieved. The resulting percentage of spatter pixels per column or Spatter Percentage (SP) value was then determined. From Fig. 4.4d, it can be observed that the spatter distribution is more significant along the x direction with minor orthogonal scattering. The amount of spatter detected is seen to decrease with the distance transported in the $-x$ direction. Spatter particles were also detected above and below the scanned regions.

(a)

(b)

(c)

(d)

Figure 4.4: Typical images obtained at the tenth layer: (a) before and (b) after laser scanning (post perspective transformation), (c) result of absolute difference between image (a) and (b), (d) after application of Renyi entropy thresholding. Figures (c) and (d) have a resolution of 1272×2544 pixels.

SP of individual layers

To investigate the effect of number of layers on the SP, Fig. 4.5 was plotted. For both plots, it can be seen that there is a clear increase in SP with the number of layers. This is especially evident for column D at the 67 % gas pump setting, by as much as 77.0 % from the third to the tenth layer. However for column C, the SP remains relatively constant. Columns A and B also showed relatively lower changes in SP as the number of layers increased.

From Fig. 4.5, the standard deviation values are seen to generally decrease for all columns with the number of powder layers. An example would be for the gas pump setting of 67 % and at column A where the standard deviation value decreased from 5.30 % for the third to 2.99 % for the tenth layer. Also the plots seem to be approaching

a steady state where the fluctuations in the mean values and also standard deviation diminish with the number of layers. As such, the SP values for layer number 10 was chosen to be evaluated in this study.

(a)

(b)

Figure 4.5: Plot of mean SP and standard deviation at different layer numbers for gas pump setting (a) 60 % and (b) 67 %.

Effect of gas flow velocity on SP

To illustrate the effect of the gas flow velocity, Fig. 4.6 was plotted. SP values are seen to be gradually decreasing from column D to A. For columns C and D, SP values were greater at higher gas pump setting by as much as 7.40 % for the latter. However, lesser spatter was detected for column A at this gas flow velocity with column B showing similar SP values. Thus, increasing the gas flow velocity does not correspond to a lower amount of spatter detected by the camera.

Figure 4.6: Bar chart of mean of summed up pixels and standard deviation representing spatter particles for each column from A to D for the tenth layer.

The illustration of the bar chart from Fig. 4.6 serves to provide consistency in the reporting of data together with the mass and size distributions as seen in Fig. 4.8 and 4.9. The main reason being that the spatter was collected and analysed in batches of powder collected from each segmented column. Nonetheless, to gain a better understanding of the processed images as a function of x , Fig. 4.7 was plotted. Each column was refined to 100 pixels in width. SP values are seen to be gradually decreasing away from the scanned region. There is also no significant difference between the SP for both gas pump setting values since the standard deviation error bars overlap. However, at the higher gas flow velocity, it is shown that slightly higher SP is recorded along the x axis.

4.3.2 Distribution of spatter mass on powder bed

To illustrate the effect of the gas flow velocity on mass of spatter, the spatter collected in each column was calculated and the mean was plotted as seen in Fig. 4.8. There is a general decrease from column D to A for both cases. However, this trend is more distinct at the higher gas pump setting. It can be clearly seen that increasing the gas flow velocity led to the highest increase in mass values by as much as 25.5 % in column C. For column

Figure 4.7: Plot of mean of summed up pixels and standard deviation representing spatter particles for columns of 100 pixels width or 6.29 mm. The edge of the scanned region corresponds to $x = 0$ mark.

D, mass was slightly greater by 3.63 % at the lower gas pump setting. However, the effect of increasing the gas flow velocity has led to an increase in mass of spatter distribution. Further analysis is provided in the discussion section.

Figure 4.8: Bar chart of mean of summed up mass and standard deviation for each column from A to D.

4.3.3 Distribution of spatter particle size on powder bed

The mean diameters are reported in the form of bar charts in Fig. 4.9. The largest particles were deposited closest to the scanned regions with values of $143.1 \pm 22.6 \mu\text{m}$ and

$155.9 \pm 27.5 \mu\text{m}$ at 60 and 67 % gas pump settings respectively. Also, the decrease is more gradual at the lower gas pump setting. The increase in gas pump setting has led to the deposition of spatter particles with larger diameters downstream of the flow, which could explain the proportional relationship with the mass distribution as seen in Fig. 4.8.

Figure 4.9: Bar chart of mean diameter and standard deviation for each column from A to D.

4.3.4 Correlation between spatter mass and percentage of spatter pixels (SP)

To evaluate the effectiveness of the image processing of the powder in identifying the spatter, data from the third layer was analysed and compared against the masses of the spatter which served as the ground truth. In Fig. 4.10 below, the dependent variable or response is the SP while the independent variable is the mass of the spatter.

To establish their relationship quantitatively, the correlation coefficient (R) for regression was obtained. The data from the third layer was plotted, giving a R value of 0.46 which shows that there is a moderately positive linear relationship between SP and the masses of spatter. As such, the images captured and processed are deemed to be acceptable in predicting the amount of spatter deposited on the powder bed.

It should be noted that the resolution of the images obtained using the camera were deemed not suitable for a similar plot for spatter size and SP due to the significant difference in scale between the spatter particles and that of the images.

4.3.5 Statistical tests

To statistically evaluate the effectiveness of the argon gas flow in transporting the spatter in the $-x$ direction, the mean masses, sizes of spatter and SP from column A to D

Figure 4.10: Plot of percentage of spatter pixels against mass of spatter for regions D to A.

were subjected to two-sample t-tests with a Type 1 error probability $\alpha = 0.05$ with the number of observations, $n = 4$. The images used for SP determination in the t-tests were obtained from that of the third layer. The third layer was identified to be the first layer where the spatter could be generally observed and was minimally affected by protruding spatter from the previous layer, especially for cell D2 as seen in Fig. 4.5. The results of the t-tests are found in Table 4.2 below.

It can be seen that since the p-value for every case is greater than 0.05, the values quantified when the gas pump was set to 60 % and 67 % are not statistically significant in terms of their difference. Therefore, while increasing the gas pump setting led to a general increase in the mean values, it did not contribute to a significant increase in the distance of spatter transported.

4.4 Discussion

4.4.1 Effectiveness of image processing

To establish the effectiveness of the image processing methodology, the correlation coefficient between SP and spatter mass, was plotted as seen in Fig. 4.10, with an R value of 0.46. The reason for illustrating the correlation between SP and spatter mass is that mass is a collective property of the spatter, which is similar to the number of pixels representing spatter. On the other hand, the spatter sizes were reported as mean diameter

Table 4.2: Statistical table for t-tests

Spatter Property	Gas pump	60 %		67 %		p-value
	Column	Mean	Variance	Mean	Variance	
Mass [mg]	A	116.4	1.3	127.9	0.7	0.313
	B	125.4	0.5	147.1	2.0	0.207
	C	127.1	1.4	159.5	2.0	0.155
	D	178.0	0.9	171.8	0.8	0.396
Diameter [μm]	A	96.1	19.4	113.9	2077.2	0.247
	B	108.5	298.4	112.7	1389.2	0.422
	C	122.0	1207.7	116.4	2064.7	0.426
	D	140.1	713.3	155.9	752.5	0.240
Percentage [%]	A	6.5	7.1	4.4	0.1	0.106
	B	10.4	6.9	10.3	1.3	0.471
	C	21.1	9.9	23.0	8.2	0.208
	D	36.4	2.9	39.5	9.0	0.090

values of the sampled individual spatter particles within each column obtained via optical microscopy. The high variance in terms of the spatter diameter also showed that improvements could be made in reporting the sizes of the spatter. One way to utilize the spatter size in order to reflect a better correlation with the SP would be to obtain the percentage surface area of spatter. This would require in-situ micro images of all the spatter particles following their deposition on the powder bed. However, due to the limitation inherent in the camera used during the experiments, such data acquisition proved to be unattainable. The same explanation could be applied with regards to the number of spatter particles, since it is nearly impossible to count them individually. Thus, mass of spatter served as a better variable in providing a more reliable ground truth property.

The correlation coefficient of 0.46, means that there was a clear positive correlation between the collected spatter mass and SP. This established our image processing method as an effective quantitative method to study the amount of spatter without disturbing the powder bed. We noted however that the correlation was not overwhelming. Despite this, a crucial limitation during the spatter collection is the possibility of spatter particles with diameters smaller than $63 \mu\text{m}$ not being sieved out which could possibly explain the low R value of 0.46. From a study conducted by Wang et al. (2017), three types of spatter have been identified. In our study, droplet spatter was mainly analysed, due to

their sizes being greater than the fresh powder, making it practical to be collected. However, the remaining two types of spatter; metallic jet and powder spatter was possibly deposited on the powder bed. Their work is supported by that of Ly et al. (2017) where it was reported that three different types of spatter ejections had been recorded from high speed cameras. The sizes of such uncollected particles could have been smaller than $63\text{ }\mu\text{m}$ since it was reported that a droplet of diameter $8\text{ }\mu\text{m}$ was ejected at approximately 18 m/s .

It has been shown that visually, there is a general decrease in the amount of spatter in the $-x$ direction. The reason for the detectability of the spatter by the naked eye is due to the stark difference in contrast of spatter to fresh powder. Spatter particles appeared larger and darker due to the formation of surface oxides. This difference in contrast proved to be crucial in the image processing which detected the spatter following the application of the Renyi entropy thresholding method. However, due to the larger mean diameter of the spatter as seen in Fig. 4.9, as compared to the input layer thickness of the powder bed ($100\text{ }\mu\text{m}$), the images taken could have revealed protruding spatter that had been deposited on previous layers. This could validate the increase in SP for column D as seen in Fig. 4.5 since the diameter of spatters were the largest. On the same layer studied, overlap of spatter particles was also observed and thus the underlying spatter were not captured by the camera. Therefore, such inaccuracies along with the cumulative effect of spatter protrusion from previous layers could potentially decrease the reliability of the image processing technique. Additionally, improved lighting conditions where the illumination gradient is regular, to minimise shadows and misclassification of spatter on the powder bed is critical to obtain a more optimal bi-level image (Lu & Tan, 2007; Parker, 1990).

Lastly, from Fig. 4.7, it was shown that unlike the quantification of mass and size of spatter where the particles had to be collected and sieved, image processing allows the user to analyse spatter at smaller and specific positions on the powder bed. With a higher resolution camera, even narrower regions as compared to the 100 pixel width used in Fig. 4.7 could be applied. This would allow optimal placement of parts on the powder bed in order to minimise contamination during SLM. The above discussion also hints that image analysis, besides offering the advantage of being an easy to set up and in-situ non-destructive method, could potentially be the most accurate method to quantify spatter distribution. However, this possibility must be further tested in future research, using other independent methods to quantify the spatter distribution.

Figure 4.11: Plot of percentage of Stokes number for regions D to A. The characteristic length L_0 is taken from the center of the scanned region.

4.4.2 Transport of spatter by argon gas flow

Validation with Stokes number

The transport of spatter by argon gas flow is essentially a form of gas-solid flow, specifically where the particle dynamics differ from that of the fluid. This is due to the particle inertia which could possibly cause selective concentration, cluster and separation (Segré & Silberberg, 1962; Tirumkudulu et al., 1999). To verify the distribution of spatter downstream of the gas flow, the Stokes number (Stk) is used. The Stk number is a dimensionless number which characterises suspended particle behaviour in the fluid, in this case argon gas. It is defined as the ratio of the characteristic particle time to that of the flow: $Stk = \rho_p d_p^2 U / 18 \mu_f L_0$, where ρ_p is the particle density, d_p is the particle diameter, μ_f is the fluid dynamic viscosity and L_0 is the characteristic length. As a guideline, for very fine particles which satisfy $Stk \ll 1$, the particle follows fluid streamlines, in other words, perfect advection or pure suspension (Kaftori et al., 1995). Otherwise, for $Stk \gg 1$, the particle is dominated by inertia and continues along its initial trajectory where possible particle-wall and particle-particle collisions occur (Taniere et al., 1997).

Previous studies showed that surface oxides formed on the spatter due to the oxidation of the most volatile elements in the alloy were only several μm thick (Simonelli et al., 2015). In this work, the density of the spatter was determined based on the assumption that the surface oxides were relatively negligible as compared to the bulk of

the particle. As such, the value of ρ was taken to be 2700 kg/m^3 , which is equivalent to that of the fresh powder. For the other parameters, U was found to be 1.41 and 1.57 m/s for gas pump settings 60 and 67 % respectively, $\mu_f = 2.23 \times 10^{-5} \text{ kg/(ms)}$ and L_0 varied from 40 to 160 mm.

The computational results of the Stk number plotted in Fig. 4.11 shows an exponential relationship established where the standard errors of non-linear regression (S) obtained were 0.90 and 1.46 at the 60 and 67 % gas pump settings respectively. The Stk ranges from 0.43 to as high as 9.19. Particles with Stk greater than 1 are seen to travel not further than approximately 120 mm from the scanned region at the lower gas velocity. At the 67 % gas pump setting, this distance also increased to 130 mm, representing a 8.33 % increase in spatter transport distance. Thus, it can be seen that this range does not reveal a clear cut explanation on the nature of the spatter transport by the gas flow. Indeed, a combination of both the effect of spatter transport and the particle inertia during the particle laden flow could have most likely taken place. However, since the diameter of spatter is a function of Stk , it shows that the distribution of spatter is influenced by its size. For spatter with Stokes number lower than 1, the effect of the gas flow would dominate the particle inertia and therefore such smaller particles would be transported further downstream from column D to A, as seen in Fig. 4.9 (Eaton, 2009).

For larger particles, generally there would be a correspondingly higher Stk value. By assuming that the density is independent of other variables, their mass would then have a positive linear relationship with the size of the spatter. As such, these particles would settle out of the gas flow earlier, since the high inertia which is directly proportional to its mass as related by Newton's first law, would overcome the effects of the gas flow. Additionally, gravitational forces would act to a greater extent of the heavier particles, causing them to get deposited closer to the scanned sites. Another explanation could also be that for the same magnitude of recoil pressure, the larger molten droplets would be ejected at a lower initial momentum compared to their smaller counterparts, hence lower initial velocities would not allow such heavier spatter particles to penetrate the crossflow deep enough to be transported far before being deposited on the powder bed.

It can be seen from Fig. 4.11 that at 67 % gas pump setting the exponential plot is always higher. This corresponds to the relationship between the gas flow velocity on spatter detected from the images in Fig. 4.7 and also on the mass and size distributions in Fig. 4.8 and 4.9 respectively. With this, we can deduce that in general, the larger spatter with correspondingly larger Stk did not effectively follow the inert gas flow in the $-x$ direction. Possibly, a larger fraction of spatter did not deposit near the main central region of accumulation but instead would scatter along their own respective trajectories. As a result, such anomalous spatter particles were not detected successfully by the camera leading to the low R value of 0.46. Thus, further developments in terms of accurately capturing the spatter particles by using a more advanced lens or camera is

critical in order to effectively assess the spatter distribution visually.

Wall surface roughness introduced by the presence of the powder bed also induces velocity fluctuations on the crossflow. It was shown that in the case of particle laden flow, the streamwise component of the particle r.m.s velocities did not differ significantly, for the case of 60 and 130 μm particles (Taniere et al., 1997). Due to the saltation effect coupled with the wall surface roughness, particles travelling upwards have a smaller horizontal velocity as compared to downward moving particles. This is due to the latter being accelerated by the fluid flow. In their work, it was also reported that the particle velocity fluctuations could have been affected by their size distribution since smaller particles experienced lower fluctuations. Additionally, Sommerfeld & Kussin (2003) reported that increasing wall roughness significantly affects the transport velocity of particles where their fluctuating energy is intensified. Due to the particle collision with the wall and in this case the powder bed, rotational effects could also take place, imposing the Magnus lift force, as studied by Hussainov et al. (1996).

Interestingly, when the linear plots from Fig. 4.11 are extrapolated, the exponential curves converges approximately at the 320 mm mark. Thus the region where the Stk value reaches zero, which is the case where the particles follow the gas flow streamlines completely, would be near the edge of the powder bed or substrate. This coincides critically with the limitations inherent in all variants SLM Solutions Group AG's machines, where the powder bed has been restricted to 280 mm for the x dimension due to the overall effectiveness of the gas flow in transporting spatter away from the powder bed (SLM, Accessed: 2018-01-29). In other words, should a spatter particle with Stk value of 0 begin its transport by the inert gas flow at the edge closest to the gas inlet, the furthest distance it would theoretically cover is 280 mm, as suggested by the exponential plots in Fig. 4.11.

Spatter ejection profiles

Prior to being transported by the inert gas flow, the spatter gets ejected from the melt pool due to the coupling effects of recoil pressure and Marangoni convection within the melt pool (Khairallah et al., 2016; Qiu et al., 2015). The ejection profiles have been qualitatively reported in earlier studies where high speed cameras were used to capture the images (Bidare et al., 2017a; Ly et al., 2017; Wang et al., 2017). It can be seen that when the laser scanning speed increases, the ejection profiles would generally shift from vertically upwards (90°) to a relatively smaller angle to the powder bed (Ly et al., 2017). Also, the images were taken in a two dimensional plane ($x - z$) and information on whether spatter was ejected in the y direction was not reported. Such information that has not been recorded could determine the deposition of spatter on the powder bed.

The reason the ejection profiles, specifically in terms of the angle and velocity, are critical in the distribution of spatter is that their inertia at the initial ejection could prove

Figure 4.12: Schematic of spatter ejection profiles from melt pool and the effect of gas flow in the particle trajectories.

to be influential in the eventual deposition locations. Fig. 4.12 shows how the trajectories of the particles would extend from the presence of the gas flow. For example, for the same particles mass and size, those that ejected at high velocities and large angles would have high kinetic energies which translates to a higher trajectory in the absence of gas flow. On the other hand, those ejected at lower angles would not get deposited far from the scanning sites. Bidare et al. (2017a) observed that the ejected particles possessed sufficient upwards momentum to not be subjected to the crossflow in the initial phase of their trajectories. However, gravitational forces would bring them back down and eventually be carried by the inert gas crossflow. Regardless, in SLM, the presence of the gas flow would transport these particles in the further downstream in the $-x$ direction, and therefore their distribution would depend more heavily on the Stokes number as explained earlier.

A full study of the effects of the inert gas crossflow, laser power and speed on the spatter distribution is beyond the scope of the current study, hence the lack of experimental results for cases at other values. Nonetheless, the current work would be able to serve as a datum for future research which could incorporate such variables.

4.4.3 Theoretical considerations

Studies by other researchers concluded that oxide layers tend to develop on the solidifying molten droplets upon ejection (Anwar & Pham, 2017; Simonelli et al., 2015). The increase in mass and size of the spatter attributed to oxidation could potentially affect the initial trajectory of the spatter since they could disperse out of the flow at a faster rate downstream. Spatter distribution during the SLM of materials with little or no elements with high affinity to oxidise such as titanium alloy, Ti-6Al-4V could also be investigated on. Despite this, it should be noted that the thickness of the oxide layers are in several as μm reported by Simonelli et al. (2015) which is relatively insignificant considering that

the spatter size can reach up to 200 μm in diameter.

A more notable contribution for the spatter sizes is the magnitude of recoil pressure present during SLM. Andani et al. (2017a) was the first to report on the spatter sizes as a result of double laser scanning. It was revealed that when two lasers were in use, spatter diameter ranged from 200 to 720 μm as compared to single laser scanning where the diameter had a range of 120 to 620 μm . With multiple lasers, a greater build up of recoil pressure is generated, producing spatter particles of greater size. In a separate study, Andani et al. (2017b) also showed that when laser power increased from 250 to 375 W, a greater number of spatter was produced. Wang et al. (2017) also showed how laser energy significantly influences spatter generation, where the spattering intensities increased with higher energy. Therefore, future research could involve investigating the effects of laser energy, which includes laser power, speed and also the number of lasers, on the spatter distribution on the powder bed.

On the theoretical side, the transport of spatter by the inert gas flow needs to be modelled mathematically as a multiphase flow while considering the ejection profiles of the spatter from the moving and solidifying melt pool as proper boundary conditions. Fundamental conservation equations for mass, momentum and energy would need to be closed appropriately with the suitable models. The flow conditions whether laminar or turbulent could also play a crucial role in determining the depositing locations of the spatter on the powder bed. Additionally, convection effects which are affected by the temperature of the substrate or the effects of increasing powder layers should also be investigated. Other forces that should be considered are the drag, gravitational and buoyancy forces. Therefore, gas-solid flows in a horizontal configuration could be adopted as suitable models in order to closely replicate the transport phenomena.

4.5 Conclusion

In this study, three main results have been established. Firstly, the results from the image processing showed a positive linear relationship with the mass which was treated as the ground truth. However, further tests have to be carried out to improve the credibility and suitability of the proposed method as a simple yet efficient in-situ spatter characterisation technique in SLM. Nonetheless, the current image capturing and processing methodology has proven to be able to serve as an immediate assessment tool to quantify the distribution of mass of spatter on the powder bed.

Secondly, it was shown that the largest spatter in terms of mass and size were observed to be deposited closest to the scanned regions and gradually decreased in the $-x$ direction or downstream of the argon gas flow. Spatter particles were predominantly observed along the scan direction, with minor orthogonal distributions. The increase in gas velocity led to an increase in the transport of heavier and larger spatter, resulting in

a more even distribution downstream of the gas flow.

Lastly, the established exponential decay in the Stk number with respect to the distance travelled by the spatter particles, elucidated the limitations in the effectiveness of the inert gas flow in removing the undesired contaminants from the powder bed. As such the reported data for the spatter distribution in SLM of AlSi10Mg could prove to be critical in optimising the gas inlet and outlet designs, in order to successfully eliminate any presence of spatter from the powder bed over larger distances.

Chapter 5

Simulations of spatter transport by inert gas flow

In this chapter, simulations of spatter particles into the CFD domain (SLM chamber) were performed. Lagrangian tracking was applied to map the trajectories of the spatter particles under the influence of the inert gas flow which was modelled using the Eulerian Method. The full work in this chapter has been submitted to the "International Journal of Multiphase Flow".

5.1 Introduction

During SLM, a host of multi-physics processes occur simultaneously; heating, melting, evaporation, solidification and also spatter ejection from the melt pool. Previous studies have attempted to elucidate the causes of the spattering either via recoil pressure or entrainment of such particles into metal vapour and plasma plumes. However, the transport of deleterious by-products which include spatter as seen in Fig. 5.1, is often neglected. Insights into the spatter transport by the gas flow will undoubtedly be critical during the design of such systems for commercial SLM machines, especially when the effective removal of spatter is crucial to minimise contamination over a large powder bed. For such cases, the spatter has to be transported over a further distance. Since it is significantly computationally expensive to model multi-physics processes concurrently, the main focus of this study is on the simulations of the spatter removal by the inert gas flow during SLM. A DPM approach is undertaken for the simulations of solid spatter particles in gas cross-flow. The simulation results were then validated with an earlier study on spatter mass and size distributions on the powder bed, specifically in regions A to D as labelled in Fig. 5.1 (Anwar & Pham, 2018).

Figure 5.1: Schematic of spatter ejection from melt pool and its transport by the inert gas flow (green arrows) in the $-x$ direction. Spatter distribution in regions marked A to D will be the main areas of interest in this study.

5.2 Numerical modelling

The transport of spatter particles by the inert gas flow is deemed as a gas-solid flow. Dilute flow is considered where the volume fraction is less than 12 % (Krishnan, 2012). In this case, one way coupling takes place where the particle motion is generally controlled by the lift and drag forces acting on them. This is as opposed to dense flow, where the particle motion is significantly influenced by particle-particle collisions such as in hoppers, fluidized beds and pneumatic transport applications. In the Eulerian-Lagrangian model, CFD is used for the gas flow which involves the conservation of mass and momentum while the spatter particles are modelled using the DPM which involves the momentum conservation equations. With regards to CFD, the fluid domain is treated as a continuum, while DPM tracks particles through the flow field. Coupling is often adopted to account for the interaction forces between the particles and fluid. In this case, one-way coupling is used since the gas solid flow is assumed to be dilute (low volume fraction of particles) (Kloss et al., 2009).

5.2.1 CFD

For fluid flow which are wall-bounded and have small mean pressure gradients, the turbulent $k - \varepsilon$ model is utilised. The transport equations for the turbulence kinetic energy (k) and that of the dissipation rate of ε (ε), for the realizable $k - \varepsilon$ model as proposed by Shih et al. (1995) and validated by Kim et al. (1999), are given as

Turbulent kinetic energy transport equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon \quad (5.1)$$

Energy dissipation transport equation:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} G_b \quad (5.2)$$

where G_k and G_b refer to the turbulence kinetic energy generation due to the mean velocity gradients and due to buoyancy respectively. μ_t is the eddy viscosity, and constants $C_{1\varepsilon} = 1.44$, $C_2 = 1.9$, $\sigma_k = 1.0$. $C_{3\varepsilon}$ refers to the degree to which ε is affected by the buoyancy of the fluid flow as studied by Henkes et al. (1991). However, the buoyancy force given by $\vec{F}_B = m_p \frac{\rho}{\rho_p} g$ in this gas-solid flow simulation can be neglected since $\rho/\rho_p \ll 1$ (Sommerfeld, 2010). Lastly,

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \eta = S \frac{k}{\varepsilon}, S = \sqrt{2 S_{ij} S_{ij}} \quad (5.3)$$

5.2.2 DPM

In this study, the DPM was applied where the particles are tracked throughout the flow field in a Lagrangian manner. DPM has been reported to be appropriate for modelling dilute particle-laden flow (Mezhericher et al., 2011). It was also implemented by Philo et al. (2017) in their study of spatter removal by the shielding gas in SLM. For the case of dilute gas-solid flow with low particle volume fraction, particle-particle interactions are neglected and one-way coupling is considered. This would reduce the computational requirements of the simulations as it would be possible to inject the particles simultaneously in the domain.

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

$$\frac{d\vec{u}_p}{dt} = \frac{\vec{u} - \vec{u}_p}{\tau_p} + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} + \vec{F} \quad (5.4)$$

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

cosity and τ_p refers to the particle relaxation time (Gnanavelu et al., 2011) and is defined as:

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_D Re} \quad (5.5)$$

For smooth particles, the drag coefficient C_D (Morsi & Alexander, 1972) is:

$$C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re} \quad (5.6)$$

where the constants a with subscripts are applied over several ranges of Re .

Re is the relative Reynolds number and is given as:

$$Re \equiv \frac{\rho d_p |\vec{u}_p - \vec{u}|}{\mu} \quad (5.7)$$

5.3 Simulation set-up

The simulation set-up in this study is based on the work conducted by Philo et al. (2017). Three-dimensional simulations were performed using the commercial software, ANSYS Fluent 18.2. The computational domain was scaled to be a 1:1 model in terms of the length (x axis) and height (z axis) of the actual SLM 280 chamber seen in Fig 5.2a, with dimensions of 425×386 mm. In this study, the depth (y axis) was limited to 140 mm since in our previous experimental work, the region for spatter collection was set to be 40×120 mm to account for possible depositions of spatter along the y directions. As such, the modelling of the suction pipes and recoater tank were not accounted for during the simulations. Particle-particle interactions were neglected and it was assumed that the particles were spherical and non-reacting.

Since the spatter ejection occurs at the powder bed, it is assumed that the deactivation of the top gas inlet would have insignificant effects on the spatter transport. The main function of the gas flow originating from the top inlet is to minimise deposition of condensate and other by-products on the lens of the lasers. Thus, to reduce the computation costs, argon gas flow was only initialised at the bottom gas inlet as illustrated in Fig 5.2b.

(a)

(b)

Figure 5.2: (a) Actual front view SLM 280 chamber and (b) 3D domain used in simulations.

5.3.1 Mesh independence test

A mesh independence study was performed with three mesh settings of coarse, medium and fine with maximum element sizes of 10, 5 and 2.5 mm respectively using the cut cell method. To satisfy the convergence, the first condition set was that the residuals reduced to 10^{-3} . Secondly, a line surface was applied at the edge of the powder bed to monitor the velocity profile of the inert gas flow. This is to determine that the upstream

flow has reached a steady state before the introduction of spatter particles. The energy equation was not accounted for during the mesh independence study to neglect computations on natural convection within the domain. Only after convergence were the spatter particles injected into the domain from the designated position on the powder bed. The simulations were then resumed until all the particles had been accounted for.

5.3.2 Boundary conditions

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

As seen from Table 5.1, the temperature of the substrate is prescribed as a heated plate. Due to its relatively high temperature as compared to that of the cross-flow fluid (taken to be 25 °C), natural convection would take place during SLM. A symmetry boundary condition was also set at the side walls of the domain to account for the zero-shear slip. To reduce computation costs, the regions A to D on the powder bed were set to "trap", in order to stop the trajectories of the particles when in contact with these regions. The same condition was also set to the walls.

In the experiments, the laser scanning region comprised of multiple unidirectional vectors. However, in this study, the dimensions of the ejection sites were 80×0.1 mm (in the x and y axis respectively). The length of 80 mm corresponds to a single scan vector as applied in our earlier work (Anwar & Pham, 2018), while the width of 0.1 mm or 100 μ m represents that of a single melt pool.

5.3.3 Initial conditions for spatter ejection profiles

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

Table 5.1: Fluid properties and chamber settings

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

Particle size distribution

It was reported that there are three main types of ejected particles during SLM based on their corresponding ejection mechanisms. The first is due to the recoil pressure exerted on the melt pool surface, causing molten droplets to be ejected at the edges of the melt pool. The other two ejections are due to the entrainment effects and are ejected as hot and cold particles, depending on their initial ejection locations from the local scanning regions. As reported by Ly et al. (2017), 15 % of the spatter particle ejections are due to recoil pressure, 25 % from cold and the remaining 60 % are hot ejections. In their work, the hot and cold ejections were stated to have diameters no larger than the fresh powder, at 30 μm , while the size distribution of the particles ejected due to recoil pressure were comparable and some were even larger than the fresh powder.

However, in our earlier experimental study (Anwar & Pham, 2018), all the analysed particles were bigger in size than the fresh powder as particles smaller than 63 μm had been sieved out. Therefore, we attribute the sizes of the collected particles to be due to possible coalescence effects between molten droplets before solidification, and also sintering between hot ejections as observed by Ly et al. (2017). The application of a greater layer thickness of 100 μm could have also led to the ejection of droplets with larger volume.

To ensure that the simulations follow the experiments as closely as possible, the spatter particle ejection profiles in terms of the size distribution and its corresponding ejection angle and speed were extracted from literature. The particles were spherical with their density set to 2700 kg/m^3 , which assumes that the molten droplets have solidified. The particle size distributions at each gas pump setting were obtained using optical microscopy and is seen in Fig. 5.3.

To reduce computational costs, the size distribution of the spatter particles injected into the domain were assumed to be similar regardless of the inert gas pump setting. Thus, for each bin or group of sizes in Fig. 5.3, the average number of particles between the two gas pump settings were obtained. The determined number of particles were then selected randomly correspondingly for each bin.

Ejection angles

Secondly, the ejection of hot spatter particles was set to be in the $x - z$ plane only. There is a lack of data on the ejection angles of spatter generation in literature. In this study, the range for the ejection angles was extracted from video data as recorded by Bidare et al. (2017a) and plotted in Fig. 5.4. In their work, Schlieren high speed imaging was used to capture the trajectories of hot particles expelled by the laser plume. This includes entrained hot powder and also ejected molten material from the melt pool due to recoil pressure. The laser power and speed was set to 200 W and 1 m/s respectively. With a

Figure 5.3: Spatter particle size distributions obtained experimentally (Anwar & Pham, 2018).

reported layer thickness of 50 μm , the energy density had a value of 33.3 J/mm^3 .

These values were deemed to be sufficiently similar to that used in our earlier work where the laser power, speed and layer thickness of 350 W, 0.9 m/s and 100 μm respectively, giving an energy density of 32.4 J/mm^3 . Also with increasing laser power and speed, the ejection of spatter shifted from the forward, to vertically upwards and eventually directed to the rear or the opposite direction as the laser scanning. Therefore, in terms of the ejection angles, the extracted data from the high speed video is deemed to be acceptable representation of the spatter ejection for this study. However, it should be noted that the corresponding sizes of the individual spatter particles were not determined for the data in Fig. 5.4. Hence, the assumption that the particle size was independent of the ejection angle was made.

By plotting the frequency of the spatter particles against the ejection angle from the data in Fig. 5.4, the following plot Fig. 5.5 is obtained. A normal distribution curve is overlaid on the bar chart.

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

Ejection speeds via entrainment effects

Hot and cold particles are ejected due to entrainment effects as reported by Ly et al. (2017). Particles closer than two melt pool widths to the laser irradiation location are quickly swept into the laser beam region and ejected as hot particles. From Fig. 5c of the paper by Bidare et al. (2017a), it was observed that both hot ejections and molten droplets ejected due to laser induced recoil pressure were entrained by the laser plume. An impor-

Figure 5.4: Initial ejection profiles of 30 hot spatter particles extracted from Bidare et al. (2017a).

Figure 5.5: Fitting of a normal distribution plot to the ejection angles of spatter particles which were experimentally observed.

tant point to note is that the two types of high temperature ejections mentioned earlier were difficult to be distinguished from the video data. Also from the collected samples of the earlier experiments, we could not match individual particles to their original ejection mechanisms based on appearance alone. It was also assumed that since the plume was pointed fully backwards, and disrupted the powder layer behind the laser beam, even the recoil pressure driven particles would be subjected to the aerodynamic drag which pulls these droplets towards the plume (entrainment). Thus in this simulation study, both types of ejections have been categorised as entrained particles in order to reduce computational effort.

The ejection velocity due to entrainment effects as reported by Ly et al. (2017) is given by

$$v_p = v_g(1 - e^{-\frac{t}{\tau}}); \tau = \frac{2\rho_p R^2}{9\mu} \quad (5.8)$$

where v_p is the particle velocity, v_g is the gas velocity, τ is the entrainment time, R is the particle radius, ρ_p is the particle density and μ is the gas dynamic viscosity. Following the same principles, for a laser beam diameter of 80 μm and scan speed of 900 mm/s or 0.9 m/s, the particle dwell time $t = 8.9 \times 10^{-5}\text{s}$. Assuming $t \leq \tau$, $v_p \approx v_g \frac{t}{\tau}$. The plume velocity was also reported to be a few hundred m/s, and from the results on the laser plume velocity distributions by Bidare et al. (2017a), which is in agreement with that of the gas velocities reported by Ly et al. (2017). The laser plume velocity contour plots as reported by Bidare et al. (2017a) show that the velocity decreases with height, and the highest velocity is maintained at the core of the plume near the powder bed. Since the locations of the interactions between the entrained particles and the plume varies and indeterminate, the velocity of the plume at a high value of 900 m/s was applied in this study, as it is assumed that the particles would be entrained very closely to the laser beam.

The laser plume was reported to generate a radial flow field in the argon atmosphere, due to momentum conservation, exerting drag forces on surrounding particles (Bidare et al., 2017a). To reduce computation costs, the temperature dependent gas dynamic viscosity of argon is assumed to be constant at a value of 8.9 kg/(m/s) at 2000 K (Macrossan & Lilley, 2003).

Summary of ejection profiles

To conclude, the steps taken to determine the input parameters of the each spatter particle were; firstly, the size was sampled from the distribution in Fig. 5.3. Following that, the ejection angle which was assumed to be independent of the spatter size and ejection types, was determined randomly from the normal distribution in Fig. 5.5. Finally, the particle speed was computed from Equation 5.8.

Additionally, the simulations conducted did not fully account for the multi-physics

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

5.4 Results and discussion

5.4.1 Mesh independence test

The result of the mesh independence test is shown in Fig. 5.6 below. It can be seen that the medium mesh made up of a maximum of 5 mm elements generated a maximum velocity of approximately 1 m/s in the $-x$ direction. Taking into account the significantly longer time required to run the simulations using the 2.5 mm mesh elements owing to the use of more computational resources, while giving a result close to that of the medium sized mesh especially for z lower than 0.04 m, the remainder of the simulations were performed using 5 mm elements.

Figure 5.6: Mesh independence test results for coarse, medium and fine meshed domains.

5.4.2 Validation with experiment results

The actual imaging of the inert gas flow within the commercial SLM Solutions machines have not been reported in literature. From the CFD simulation results illustrated in Fig. 5.7 below, the gas flow near the powder bed is seen to be laminar throughout. Due to the presence of the step near the outlet, the flow is perturbed vertically but still continues its path to the outlet.

Figure 5.7: Steady state velocity contours on $x - z$ plane showing laminar and uniform argon gas flow near the powder bed for inlet velocity of 1.41 m/s.

Fig. 5.8 shows the trajectories taken by the spatter particles when the gas flow was initialized at 1.41 m/s. Previously, the spatter particle trajectories have been captured in 3D as reported by Bidare et al. (2017a). However, the initial paths taken by the spatter seen in Fig. 5.4 were only recorded in the $x - z$ plane, with no data recorded for spatter penetration in the y direction. It was observed that spatter ejected with a y direction vector component occurred randomly and thus were not accounted for in this study. The simulation results from this work were validated from our earlier experimental data on the spatter distribution on the powder bed as shown in Fig 5.9 (Anwar & Pham, 2018).

Validation for size distributions

The first validation with the experiment results is on the size distributions of the deposited spatter particles. It can be seen that for regions A to D, the trend in the mean spatter diameter obtained from the simulations is very much similar to that from the experiments. From Fig. 5.9b, the absolute difference between the simulation and experiment values achieved was as low as 0.6 % as seen in region A while the greatest discrepancy with a value of as high as 61.1 % was found in region C. From the data reported by Ly et al. (2017), there was a decreasing trend for both hot ejections and recoil pressure induced ejections, with increasing diameter of the particles. Thus the larger

Figure 5.8: Profiles of path trajectories for a range of spatter particles for gas flow velocity of 1.41 m/s.

spatter particles possessed lower initial velocities resulting in significantly shorter distances travelled both horizontally and vertically. Also, as seen from our earlier work (Anwar & Pham, 2018), the particles that are deposited in regions B to D had Stk numbers close to or greater than 1 due to their large diameter values which reached close to $180\text{ }\mu\text{m}$.

Despite the large contrast in spatter diameters between simulation and experiment results, a good agreement has been reached in terms of the trend of the size distribution. Future simulation studies on the transport of spatter particles by the inert gas flow could incorporate more parameters. These could include collisions between the spatter particles, rotation effects and also the recoil pressure on the ejection of spatter. Accounting for the multi-physics within and above the melt pool such as Marangoni forces, recoil pressure and vaporisation as studied by Khairallah et al. (2016), would then provide a more complete and realistic approach to the simulations, from the spatter generation to their transport by the gas flow and finally the deposition or distribution on or out of the powder bed.

(a)

(b)

Figure 5.9: Bar chart of mean diameter of spatter particles for both experiment and simulations at (a) 60 and (b) 67 % of gas pump setting.

In this current study, the ejections due to recoil pressure were neglected, such that it was assumed these particles also ended up being entrained and swept away by the metal vapour and laser plume which had velocities of up to a few hundred m/s (Bidare et al., 2017a). However, recoil pressure driven spatter which accounted for 15 % of the spatter particles in the study by Ly et al. (2017) could have resulted in more accurate results being obtained.

Based on the results reported by Ly et al. (2017), the melt pool ejections due to recoil pressure and not the entrainment effect have ejection speeds ranging from 3 to 8 m/s. In both the studies performed by Ly et al. (2017) and Bidare et al. (2017a), stainless steel powder was used as the input material. The angle of ejection of spatter particles were also projected rearwards, in the opposite direction to that of the laser beam mo-

tion. However, our previous work used the aluminium alloy, AlSi10Mg, powder with a thermal conductivity of 146 W/(mK) was used as compared to stainless steel 316L with a value 21.4 W/(mK) (Aboulkhair et al., 2014). This means that a more intense spatter generation is expected for aluminium alloy.

From the velocity-size distribution plot illustrated in the work by Ly et al. (2017), an inverse relationship was established for melt pool ejections which did not involve the entrainment effect. In other words, for spatter particles ejected due to the recoil pressure on the melt pool, the ejection velocity decreases with increasing diameter. This relationship was reported by Kaplan & Powell (2011), where it was stated that the threshold for the escape of molten droplets is influenced by the local surface tension, surface geometry, gravity and viscosity. For a spherical droplet with radius of curvature R , the surface tension pressure of a curved surface derived from the Young-Laplace equation is given by

$$\Delta p = \frac{2\sigma}{R} \quad (5.9)$$

where σ is the surface tension.

The molten droplet ejection condition is possible when the dynamic pressure which refers to the kinetic energy per unit volume of a fluid particle, is sufficient to overcome the surface tension pressure (Wu et al., 2017) and is given as

$$\frac{1}{2}\rho_L u_L^2 \geq \frac{2\sigma}{R} \quad (5.10)$$

where ρ_L is the liquid metal mass density and u_L is the vertical component of the velocity. In the study by Ly et al. (2017), where $R = 200\mu\text{m}$ and $\sigma = 1.5\text{N/m}$, the escape velocity for stainless steel 316L was found to be approximately 1 m/s which was in agreement with that reported by Kaplan & Powell (2011). Due to the uneven surface of the melt pool, it was assumed that the molten droplets were ejected normal to the local melt pool surface such that u_L represents the normal velocity component.

However, in this study the escape velocity as a function of melt diameter, which was assumed to be equivalent to the spatter diameter, is established in Fig. 5.10. The input parameters for the molten droplet escape condition is found in Table 5.2.

Table 5.2: Parameters for molten droplet escape condition

Property	Symbol	SS 316L	AlSi10Mg	Units
Density	ρ_L	6881 (Kumar et al., 2008)	2320 (Assael et al., 2006)	kg/m ³
Surface tension	σ	1.5 (Ly et al., 2017)	0.705 (Dou et al., 2008)	N/m

In this work, the temperature at which the molten droplets are ejected from the melt pool (close to the edges) was deemed to be approximately 850 °C or 1123.15 K. This value was determined based on the study by Li & Gu (2014) on the temperature distributions of the melt pool during SLM of aluminium alloys. The density was then deduced from the study reported by Assael et al. (2006) on the density of liquid aluminium as a function of temperature. The surface tension was then determined from the experimentally obtained relationship between surface tension and temperature established by Dou et al. (2008).

From Fig. 5.10, the escape velocity for AlSi10Mg spatter particles are greater than that of the SS316L across all diameter values. Up to 20 μm diameter, the velocity decreases sharply to approximately 10 m/s from an initial value of 35 m/s for AlSi10Mg. The range of ejection velocity for spatter particles with diameters 60 to 300 μm is from 6.4 to 2.8 m/s. This corresponds to the results reported by Ly et al. (2017) where the spatter diameter has an inverse relationship to the ejection velocity.

Figure 5.10: Plot of spatter ejection velocity against diameter.

Therefore, to put things into perspective, the entrainment driven ejection velocity equation (equation 5.8) resulted in particles with diameters of 130 μm and bigger to have velocities of 2.8 m/s and lower. This means that should the recoil pressure driven particles be accounted for in the simulations, their deposition further downstream of the inert gas flow and possibly outside of the powder bed due to their greater initial ejection velocities. This could lead to more accurate comparisons with the experiments.

Validation for mass distributions

The second validation is with regards to the mass distributions which has been reported in terms of mass percentage. As seen in Fig. 5.11, the discrepancies between experiment and simulation results are lower throughout all regions. At gas pump settings of 60 and

67 %, the differences range from 2.8 to 27.8 % and 0.7 to 29.7 % respectively. Therefore, an even better agreement between experiment and simulation results has been established as compared to the size distributions.

(a)

(b)

Figure 5.11: Bar chart of mean mass percentage of spatter particles for both experiment and simulations at (a) 60 and (b) 67 % of gas pump setting.

5.4.3 Effectiveness of inert gas cross-flow

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

contaminants on the laser lens would perturb the focal point of the laser beam leading to inaccurate energy input at the powder bed during laser scanning.

The trajectories of the spatter particles in the absence of the inert gas cross-flow are illustrated in Fig. 5.12. It is clear when comparing Fig. 5.8 and Fig. 5.12 that the trajectories are extended due to the presence of the inert gas flow, especially for the smaller particles, which are illustrated by the blue lines. To quantify the effect of the inert gas flow, the size and mass distributions for the case of no gas flow is compared with those including gas flow in Fig. 5.13 and 5.14. It can be observed that all of the spatter particles were deposited on the powder bed with their less steep gradient for the size distribution. For the mass distribution however, more than 40 % of the spatter particles accumulated in region D. Therefore, the presence of the inert gas flow has shown to generate a more even distribution of spatter particles downstream of the spatter injection locations or for the case of SLM, the laser scanning sites.

Figure 5.12: Profile of path trajectories for a range of spatter particles without gas flow.

As reported by Ladewig et al. (2016), the SLM process by-products were observed to deposit near the outlet, due to the regions of low inert gas flow velocities at those areas. From Fig. 5.8, it can be seen that this is indeed the case since the velocity of the gas decreases with distance over the powder bed. Thus, it was suggested that further optimisation on the designs of the gas flow inlet and outlets should be studied in order to maintain the gas flow velocities over a longer distance. The resulting favourable pressure gradient which enables the laminarization of the flow which would then allow for a more

Figure 5.13: Bar chart of mean diameter of spatter particles from simulations.

Figure 5.14: Bar chart of mass percentage of spatter particles from simulations.

effective removal of the spatter particles (Finnicum & Hanratty, 1988) .

A parametric study on the inlet and outlet designs was conducted by Philo et al. (2017), showed that the flow uniformity was indeed influenced by the gas flow inlet and outlet designs. It was also noted in their work that "the removal of spatter particulates remain unclear". Therefore, our work has proven for the first time, that even with the presence of the inert gas flow, the spatter particles were not effectively removed over the powder.

Lastly, another aspect to consider during the simulations is the distribution of spatter in the y directions. These could have originated either from the initial spatter ejections or due to the gas flow structures within the chamber. In this study, such details were not incorporated into the current work although it has been reported by Bidare et al. (2017a). An additional high speed camera simultaneously capturing the top or side view ($x - y$ or $y - z$ plane) would then provide a three-dimensional stereoscopic evidence into such insights (Krüger & Grünefeld, 1999).

5.4.4 Limitations of current work

The simulation results achieved in this current work were in good agreement with the established experimental results from our earlier work. This is in spite of the limitations which have been addressed previously. Some additional points include:

- At the macro-scale, we did not account for the presence of other obstacles/ items in the CFD domain such as the recoater tank and vacuum nozzle. The presence of such modifications to the domain would then provide a more realistic simulation scenario which could influence the transport of the spatter particles.
- Low fidelity ejection profiles since the metal vapour formation and subsequent entrainment effects were not fully modelled.
- At the micro-scale, phase transformations (solidification) of the molten droplets which occurred while being carried by the gas flow were not modelled since it was assumed that the droplets were already initiated as solid particles at the ejection site.
- Close to the melt pool, particle specific properties such as particle rotation and coalescence upon collision due to the high velocities of the metal vapour and plasma plume were observed from the video recordings of other researchers. This would have influenced the initial ejection profiles and its interactions with the inert gas flow.

5.5 Conclusion

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

Chapter 6

Conclusions & Future work

The spattering phenomenon is inherent in all laser-based manufacturing processes. The challenges associated with the spatter particles and its removal over the powder bed was highlighted as the main impediment to the development of large scale SLM machines. In this thesis, the effects of laser-spatter interactions, spatter distribution on the powder bed and also simulations of spatter transport by the inert gas flow in SLM have been conducted. The contributions of this thesis could indeed prove to be useful in the development of large scale SLM machines in the future.

Effects of laser-spatter interactions

During the SLM process, spatter particles are ejected from the melt pool. Depending on the laser power and speed, the ejection locations and profiles can vary from the forward to backward directions. By isolating the ejection of such particles to the rear of the melt pool and in the opposite direction of the laser scan, laser-spatter interactions were captured for the first time using a high-speed camera. Using ANOVA, their effects were quantified with the UTS of the printed parts. The loss in heat energy when burning the spatter particles led to the incomplete melting of fresh powder, inducing porosity within the printed parts. Subsequently, this led to the production of parts of lower quality in terms of UTS. Additionally, the accumulation of spatter particles outside of the powder bed served as an indirect indication of the magnitude of laser-spatter interactions.

Future research could comprise of both experimental and simulation-based investigations. Firstly, unidirectional scanning was applied in the experiments. It was then suggested that scanning against the inert gas flow resulted in lower occurrences of laser-spatter-gas interactions. However, this is not practical in real cases where scanning orthogonally or at an angle to the gas flow. Therefore, other scanning strategies can be tested to realise the significance of the laser-spatter-gas interactions on the quality of the printed parts. Additionally, in this thesis, only the tensile strength was analysed to

measure the printed part property. A variety of tests could be performed to further evaluate other properties such as fatigue strength, hardness and corrosion resistance. Thus, the results from these experiments could then be linked to the possible laser-spatter-gas interactions that take place during the SLM process. Finally, a simulation model could be proposed which accounts for the interactions between ejected spatter which are carried by the gas flow and the laser beam. An optimal path for the motion of the laser beam could then be simulated before the actual SLM process takes place. This would ensure parts of high quality are fabricated by minimising the occurrences of laser-spatter-gas interactions which results in wastage of heat energy and subsequently incomplete melting of the powder.

Spatter distribution on powder bed

While laser-spatter interactions took place for a fraction of the spatter particles, others continued to be transported by the inert gas cross-flow and eventually deposited on the powder bed. To characterise the spatter distribution, three approaches were undertaken. With the powder bed segmented into four columns, the mass, size and percentage covered were quantified. The proposed image processing methodology from the data collected using the simple camera set-up also served as an immediate assessment tool for spatter distribution analysis. Further investigations into the particle Stk number revealed, for the first time, scientific evidence for the limitations with respect to the widths of the powder bed, across all variants of the commercial SLM machines. The characterisation of the spatter distribution on the powder bed would serve as a ground truth for future simulation work of spatter transport by the inert gas cross-flow.

However, further experimental data on the spatter ejection profiles are required, especially for orthogonal ejections. Stereoscopic 3D vision technology can be applied to address this challenge, along with the use of Particle Image Velocimetry systems to study the argon gas flow motions within the chamber.

Simulations of spatter transport

To understand the role inert gas cross-flow and in this case argon gas, in transporting the spatter particles away from the laser-scanned regions, CFD-DPM simulations were performed. Despite considering only the entrainment driven effects on the spatter particles, the simulation results were validated by the earlier experimental data trends and produced good agreement along the $-x$ direction. However, the argon gas flow was not significantly effective in its intended role which is to remove the spatter particles completely to the outlet, hence eliminating the presence of contaminants on the powder

bed. It was also shown that increasing the gas flow velocity did not necessarily cause more particles to be absent from the powder bed.

At the micro-scale, particle-particle interactions such as coalescence, break-up and collisions of solidified droplets should be accounted for and incorporated in future simulations to provide a more realistic scenario of the spatter trajectories under the influence of the inert gas flow. Such multi-physics applied to an optimised design of the gas flow inlets and outlet could then create a more realistic model for the development of large scale SLM machines.

Interest in large scale AM processes have generated much research on the issues hindering the development of larger machines, and it is no exception for SLM. The prospects of manufacturing larger parts for the aerospace and automotive industries are deemed to be very attractive. Therefore, the findings of this thesis has contributed to that very cause. The results reported from the experimental and simulation studies of the spatter particle distribution on the powder bed could prove to be significantly and scientifically beneficial for the development of an optimised inert gas flow system. In the future, such improvements made to remove spatter particles over a larger powder bed area would realise the possibility of producing larger SLM machines capable of fabricating even larger parts than current standards.

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Appendix

Material yield strain identification using energy absorption

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S Abdul Jalil¹ , A Anwar¹, SM Chou¹ and K Tai²

Abstract

The current gold standard of identifying yield points from stress strain curves involves identifying a significant change in elastic modulus or using an arbitrary strain offset (0.1%, 0.2% or 2%) of the elastic modulus. The development of the offset method was due to the ambiguous definitions of yield point. The result is an arbitrary yield point which is prone to various human-related errors. This article presents a method to identify a unique yield point consistently using energy absorbed by the material up to first peak stress. This mathematical process idealises the stress strain curve for easy identification of the yield point. The method was tested on three possible types of stress strain curves with either a distinct yield point or without a distinct yield point (with peak stress closer to elastic region or closer to fracture). The yield points obtained by the proposed method are shown to be robust, consistent and unaffected by variations of the stress strain curves and data noises.

Keywords

Yield strain, yield point, mathematical method, numerical method, energy absorption, material characterisation

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Introduction

Various types of materials are used in various engineering practices. These materials are characterised by their material properties which allow engineers to select them for suitable applications. One such property is the material yield point. A material's yield point is defined as the onset of plastic deformation, that is, permanent deformation.¹ Knowledge of a material's yield point allows engineers to safely incorporate it into a certain product or application. One example is the design of a car's bonnet where its yield strength determines its crashworthiness.²

For all materials, the yield point is determined with the aid of an engineering stress strain curve.³ As shown in Figure 1, some materials have a distinguishable yield point. This is normally in the form of an abrupt change from elastic to plastic deformation.

However, for other materials, the transition from elastic to plastic deformation is smooth resulting in an indistinctive yield point. In such cases, the yield point can alternatively and simultaneously be defined as the following points (refer to Figure 2):

1. *Proportionality limit.* This point is the final point of the stress strain curve where the stress is linearly proportional to the strain.^{1,4,5}

2. *Elastic limit.* The elastic limit is the maximum strain at which the material behaves elastically. Stress may not be linearly proportional to the strain. For most materials, the elastic and the proportionality limits are the same or at the very least, close to each other.^{1,4,5}
3. *Estimated yield point (proof stress).* Proof stress (offset method) is commonly used to represent an estimated yield point for materials with indistinct yield point. Depending on the material, a 0.1%, 0.2%, or 2% offset is used to locate the proof stress.^{1,4-6} These offset values are, however, unjustified and are arbitrary values.⁷ For engineering metals, the most common offset is 0.002.³

Other interpretations of yield point found in the literature includes one which suggests that there is no

¹Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

²School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Corresponding author:

S Abdul Jalil, Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore.
Email: shuk0001@e.ntu.edu.sg

Figure 1. Material with distinct yield point.

Figure 2. Indistinct yield point with peak stress near elastic region. A: proportionality limit, B: elastic limit, and C: proof stress.

unique point on the stress strain curve which can be defined as the yield point⁸ with another defining yield point as the point where the stress starts to decrease with increasing strain.⁴

Researchers have sought to accurately determine the yield point of materials by using experimental, modelling and/or simulation methods. In the early days, a rather unconventional technique was developed theoretically and then validated experimentally with the use of flat-ended projectiles which were fired at specimens made of various materials such as steels, copper, iron and silver. With the analysis of the impact velocity of the projectiles on the surfaces of the specimens, the maximum acceleration of the material was given. Subsequently, the minimum yield stress value was computed.^{9,10} The work was extended to the measurements of ‘mushrooming’ of flat-ended projectiles to compute the mean dynamic yield strength of copper and low carbon steel.¹¹ The estimation of dynamic yield stress in a shocked material, which assumed a general yield and hardening behaviour suitable for application in phase-transitioning material was also developed.¹² Results gathered also had reasonable agreement with earlier estimates for predicting the dynamic yield strength aluminium. By employing uncomplicated hardness measurements using the equation $\sigma_y = (H/3)(0.1)^{m-2}$, where H and m represent the Diamond pyramid

hardness and Meyer’s hardness coefficient, respectively, the 0.2% offset method was validated in brass, steel and aluminium alloys in certain aging conditions.¹³

More recently, the temperature changes due to the thermoelastic cooling of test specimens of various metals were measured to identify the loci of initial plastic deformation.¹⁴ In the case of particulate-reinforced metal matrix nanocomposites, an analytical model was proposed for its yield point prediction which had good agreement with experimental data.¹⁵ Also, by using a micromechanical model, the yield phenomenon was elucidated based on three factors: (a) a true upper yield point, (b) common strain-hardening response, and finally, (c) the development of the triaxial stress state at the Luders front which determines the lower yield strength.¹⁶ It was also demonstrated that in particle-reinforced metal matrix nanocomposites (MMNCs), grain refinement was significant in order to determine the overall yield strength of MMNCs.¹⁷ Subsequently, by accounting for the matrix grain size and porosity, the prediction of yield strength of titanium- and magnesium-based MMNCs was performed and found to be in good agreement with experimental data validation.¹⁸ These methods are, however, concerned with the dynamic or thermal response of specific materials and therefore are not within the scope of this article.

The introduction of the offset method may be due to various interpretations and definitions of yield point that disagree with one another. This therefore leads to the development of a standardised estimation method. Currently, there is no way to determine whether the offset method leads to an over-estimation or under-estimation of the actual yield point. If it is an over-estimation, it raises safety concerns when it comes to certain applications of the material.

Despite the uncertainties and ambiguity surrounding the yield-point, a numerical method was suggested by Christensen.⁷ Christensen proposed that the yield point exists at $d^3\sigma/de^3 = 0$. What this criterion suggests is that the yield point is located at the point with the maximum decrease in the local tangent in the stress strain curve.

The objective of this article is to overcome the uncertainties related to yield point identification on experimental stress strain curves by presenting standardised method where a unique point is identified to represent the onset of material yield, regardless of the material and its manufacturing process. This method considers the energy absorbed by the material and idealises its stress response based on that. The method presented can be applied for any material with a clear elastic region. This article will then present and compare three cases together with the proof-stress and Christensen⁶ methods. The cases will have stress strain characteristics as follows:

1. Distinct yield point (Figure 1);
2. Indistinct yield point with peak stress near elastic region (Figure 2);

Figure 3. Indistinct yield point with peak stress near fracture.

Figure 4. Determining energy absorbed by material by calculating area under stress strain curve.

Figure 5. Idealised linearly elastic perfectly plastic material.

Figure 6. Identifying peak stress and corresponding strain.

3. Indistinct yield point with peak stress near fracture (Figure 3).

Energy absorption method

All materials absorb energy when subjected to deformation. The amount of energy the material absorbs per unit volume (W) at any strain value can be found by calculating the area under the stress strain curve up to that strain. An example is shown in Figure 4 where the energy absorbed by the material up to a strain ε , per unit volume, is represented by the shaded area under the stress strain curve.

The energy absorbed by a material, W , can be calculated using equation (1)

$$W = \int_0^{\varepsilon_i} \sigma_i d\varepsilon \quad (1)$$

where ε_i is strain and σ_i is the corresponding stress value.

In the linearly elastic deformation phase, the area under the stress strain curve is equivalent to the area of a triangle with the base being the elastic strain value and the height being the corresponding stress value. As the strain increases further, σ is no longer linearly proportional to ε . As indicated in Figure 2, this point is known as the proportionality limit. Beyond this point, the gradient of the stress strain decreases. For an idealised linearly elastic perfectly plastic (LEPP) material model,¹⁹ where the proportionality limit, elastic limit and yield point are all at the same strain point, the gradient of the stress strain curve immediately decreases to 0 as seen in Figure 5.

The ideal LEPP model can be used to represent a portion of any stress strain curve based on the amount of energy absorbed followed by comparing the elastic moduli (or average moduli) of the curve with that of the idealised model. Once the elastic modulus is matched, the yield point can be identified as point Y. The detailed method is described below:

1. Identify first peak stress (σ_{pk});
2. Integrate the given stress strain curve up till the strain value (ε_{pk}) corresponding to σ_{pk} to determine amount of energy absorbed (W_{pk}) as in Figure 6;
3. Assume yield strain (ε_y) can be anywhere between $\varepsilon = 0$ to $\varepsilon = \varepsilon_{pk}$;
4. Select first strain value (ε_1) (Figure 7);
5. Convert W_{pk} into a LEPP model (Figure 7). LEPP area, W_{pk} , can be rearranged to determine σ_1' as shown

$$W_{pk} = \frac{1}{2} \times [\varepsilon_{pk} + (\varepsilon_{pk} - \varepsilon_1)] \times \sigma_1' \quad (2)$$

$$\sigma_1' = \frac{2W_{pk}}{[\varepsilon_{pk} + (\varepsilon_{pk} - \varepsilon_1)]}$$

Figure 7. Converting stress strain curve up till ε_{pk} to a LEPP model based on amount of energy absorbed.

Figure 8. Calculating E'_1 and E_1 (zoomed in on Figures 6 and 7).

6. The predicted modulus (E'_1) for the LEPP model can then be calculated (equation (3)) and the modulus of the actual stress strain curve (E_1) can be estimated (equation (4)) as shown in Figure 8

$$E'_1 = \frac{\sigma'_1}{\varepsilon_1} \quad (3)$$

$$E_1 = \frac{\sigma_1 - \sigma_0}{\varepsilon_1 - \varepsilon_0} \quad (4)$$

where σ_0 and ε_0 are the stress and strain values, respectively, at the origin which are normally ≈ 0 , and σ_1 is the experimental yield stress value on the stress strain curve corresponding to ε_1 .

7. The difference in modulus (ΔE) can be calculated with equation (5)

$$\Delta E_1 = \left| \frac{E_1 - E'_1}{E_1} \right| \quad (5)$$

8. Steps 4–7 are repeated for all strain values up to ε_{pk} . ΔE is plotted together with the original stress strain curve as shown in Figure 9.

Figure 9. Identifying yield strain, ε_y , at minimum ΔE .

9. The minimum ΔE corresponds to the ε_y and respective σ_y . Therefore, the energy absorption method yield point criterion is defined as

$$\frac{\partial}{\partial \varepsilon} (\Delta E) = 0 \quad (6)$$

In other words, the yield point, ε_y , of any stress strain curve is defined as the equivalent idealised LEPP curve's proportionality limit. The equivalent idealised curve absorbs the same amount of energy up to ε_{pk} with the final predicted E' approximately equals to the final estimated E .

Case studies

This section highlights the proposed method using all the possible scenarios. The currently established methods (by observation or using offset) will be compared together with Christensen's method⁷ (published post-2000).

Case 1: stress strain profile with distinct yield point (Figure 10)

Figure 10 shows the stress strain curve for low carbon steel. The yield point can be clearly identified from the curve just by observation alone. The proposed method suggested was also applied resulting in the exact same point. Likewise, for Christensen's method.

There are two maximum points on the curve, one being the yield point itself which is the first maxima, while the other is the ultimate stress. As mentioned in the previous section, the first step when applying the proposed method is to locate the first peak stress. This case highlights that the first peak stress does not need to be the ultimate strength.

For the case where the stress strain profile has a distinct yield point, the minimum ΔE value is located at the strain value which corresponds to the first peak stress, and therefore, there will be no turning point of ΔE observed (Figure 11). For other cases, minimum ΔE usually occurs before the first peak stress; hence, the ΔE will have a turning point, as seen in Figure 9.

Figure 10. Low carbon steel stress-strain curve.

Figure 11. Minimum ΔE value corresponds to the yield point for low carbon steel.

Figure 12. Location of yield points obtained by various method on the stress strain curve of a 3D printed polymer under tension.

Figure 13. Anomalous yield point identified by Christensen's method for one of the 3D printed specimens.

Case 2: nondistinctive yield point with peak stress near elastic region (Figure 2)

Stress-strain curves in Figures 2, 4 and 6–9 have non-distinctive yield point with a peak stress relatively close to the elastic region. This curve was obtained by performing a tensile test on a 3D printed polymer with a polymeric composition of 50% TangoPlus (rubber), 50% VeroClear (plastic). Employing 0.2% offset, Christensen and proposed methods resulted in yield points as shown in Figure 12. The stress strain curve in Figure 12 is the same curve in Figures 4 and 6–9 but is zoomed in to highlight the differences of the yield points obtained by the various methods.

Christensen's and the proposed method both identified the proportionality limit as the yield point, while the 0.2% offset yield point has a slightly higher strain value by 3.60%. Similar results were observed for various specimens of the same material. However, for one of the specimens, the yield point obtained by using Christensen's method is 13.0% before the proportionality limit (Figure 13).

Comparing the stress strain curves in Figures 12 and 13, the differences are very slight. The proposed method is consistent in identifying the proportionality limit. The same cannot be said for Christensen's method. One of the possible reasons could be due the small variations in the stress values on the curve which are likely due to data noises. These variations affect how the local gradient changes and thus affecting the consistency of the Christensen's method. The proposed method, on the other hand, identifies the yield point by calculating the energy absorbed and the average modulus of the stress strain curve. Utilising multiple parameters minimises the effect of such data variations.

Case 3: nondistinctive yield point with peak stress near fracture (Figure 3)

The stress strain curve in Figure 3 was obtained from the tensile testing of aluminium alloy AlSi10Mg parts manufactured using the Selective Laser Melting (SLM) process.²⁰ The transition between the elastic and plastic region is smooth. The yield points and even the proportionality limit cannot be identified accurately by observing the curve alone. The stress increases throughout the deformation before drastically decreasing till failure. The peak stress for this case is the ultimate stress as there is only one maximum.

Three rectangular blocks were fabricated using SLM with the following input parameters; laser power of 350 W, layer thickness of 100 μm , laser speed of 900 mm/s and hatch space of 0.12 mm. The blocks were then machined to ASTM E8 specimen 3 standards and subjected to tensile testing. The proof-stress (0.2%), Christensen's and proposed methods were then applied to the stress strain curves from the tensile testing of three specimens of the same material. The resulting

Figure 14. Location of yield points obtained by various method on the stress strain curve of a 3D printed metal under tension.

Figure 15. Slight adjustment to stress strain data resulted in the same yield points for both Christensen's and the proposed method.

yield points for all specimens are similar and is as observed in Figure 14.

The yield point obtained by the proposed method and the 0.2% offset are close to each other but very different from Christensen's method (44.6% and 44.5% smaller than the offset and proposed yield strains respectively). Christensen's method is strictly based on the change in the gradient of the local tangents of the stress strain curve. The Christensen's yield points identified are also likely to be the proportionality limits but not necessarily the actual yield due to the various definitions of yield as mentioned in section 'Introduction'. On the contrary, the proposed method's yield points are based on the equivalent idealised models' yield point. Furthermore, having a yield point similar to that obtained by the offset method, a widely acceptable and utilised method, suggests that the proposed method's yield point is more desirable.

Discussion

The proposed method has been consistent in identifying a yield point similar to the 0.2% offset yield points for all cases. For case 1, no offset is required as the yield point is distinct. Case 2 highlights the dependency of the proof stress/offset method on the shape of the curve

in identifying the yield point. A slightly lower elastic modulus will lead to a higher yield strain value, a slightly higher local gradient after the proportionality limit will also lead to higher yield strain and many other factors involving the shape of the stress strain curve which may jeopardise the reliability of the obtained yield point. For cases 1 and 2, the yield strains identified by the offset method and the proposed method are comparable. This highlights the reliability of the proposed method in identifying yield points given that offset method have been used for decades to achieve the same purpose even though the obtained yield point is an arbitrary point.

Comparing the proposed method to Christensen's method, both methods are numerical approaches that offer unique quantifiable yield strain values. Both methods suggest that yield point need not be interpreted as an arbitrary point. Both methods identified the same yield points for cases 1 and 2, less one specimen (specimen 1) for case 2. This different yield points between Christensen's method and the proposed method for specimen 1 case 2 is likely due to Christensen's method being too sensitive to changes in the gradients of the local tangents.

Stress-strain curves from material testing are obtained from data points with a certain data acquisition rate. The higher the acquisition rate, the more data points are resulted which will lead to more accurate readings but may also result in data noise.²¹ Data noise is basically a fluctuation of the data values. Although the data noise with the stress strain data used in this article is minimal, it still affected the yield point obtained by Christensen's method for specimen 1 in case 2. A slight adjustment to the data points for the stress strain curve from Figure 13 will result in the energy and Christensen's method having the same yield point as seen in Figure 15.

For case 3, the yield point obtained by applying Christensen's method is significantly earlier as compared to the proposed method's yield point and proof stress. As mentioned previously, this is due to the second derivative identifying the first highest change in local tangent gradients as the yield point, whereas the proposed method fits the stress strain curve to an ideal curve based on the energy absorption before identifying the yield point. In other words, the proposed method considers wider range of factors (first peak stress- σ_{pk} , energy absorbed- W_{pk} , and average modulus- E_n , etc.) to identify a yield point while Christensen's method is only concerned with the change in local tangents ($d^2\sigma/de^2$) of the stress strain curve.

Conclusion

The purpose of this article is to demonstrate the reliability of the energy absorption method in identifying a material's yield point. The stress strain curves were classified into three categories with the first having a

distinct yield point, while the second and third having nondistinctive yield points.

Regardless of the stress strain profiles, the yield points were obtained by idealising the stress strain curves up till the first local peak stress. The proposed method accurately identified the yield point for the stress strain curve with a distinct yield point. For the second and third stress strain profiles, the proposed method consistently identified the yield points close to the yield points obtained via 0.2% offset.

Despite being a widely acceptable method, yield points identified using the offset method are still very susceptible to human errors which includes the error involving the identification of the elastic modulus (E). Different people might identify different points to measure E from thus leading to varying values which will in turn affect the measured proof stress. The proposed method is free from any errors as it is purely a mathematical method.

Christensen's method was compared to the proposed method and Christensen's yield points are not as consistent as those identified by the proposed method (case 2) and/or too far from the proof stress values (case 3). As seen in Figure 14, the proposed method's point is closer to the 0.2% offset yield and less susceptible to data fluctuations. This is the case for all cases hence proving its reliability and consistency. However, when conservative yield strains are desired for safety concerns, Christensen's method may be useful, but it may also lead to significant underutilisation of the material's strength.

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ORCID iD

S Abdul Jalil <https://orcid.org/0000-0002-8227-6101>

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