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Selective Laser Melting of AlSi10Mg: Effects of scan direction, part placement and inert gas flow velocity on tensile strength

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Abstract

The effects of laser scan direction, part placement and inert gas flow velocity on the tensile strength of Aluminium alloy, AlSi10Mg parts manufactured using Selective Laser Melting (SLM), were studied. The scan direction, either in the same or opposite direction to the gas flow was the primary factor of interest due to the possible laser-spattered powder-gas interactions leading to energy loss while scanning the powder bed. The effects of flow velocity on tensile strength had shown to be more significant than part placement. It was found that scanning against the gas flow resulted in better part quality, as quantified by a higher Ultimate Tensile Strength (UTS). This relationship was interpreted and discussed based on other observations, such as the quantity of accumulated spattered powder near the outlet, images recorded using high-speed cameras, SEM-EDS tests, etc. Hence, the results suggest a concrete modification to existing scanning strategies with respect to the inert gas flow in SLM to improve part quality.

Keywords: SLM, AlSi10Mg, tensile strength, spattered powder, gas flow, scan direction

1. Introduction

There are many laser material processing techniques that generate spattering, such as laser drilling, cutting and welding, and SLM is no exception. It has been agreed that in general, laser spatter is due to the pressure exerted by the plasma plume on the melt pool and has detrimental effects on the part properties. Thus studies have been made to minimise spatter generation. In SLM, the removal of spattered powder from the powder bed is critical in ensuring a good build quality of the printed parts.

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Figure 1: **A:** Schematic of spattered powder generation during SLM. **B:** Snapshot of the powder bed after scanning. The greyish spattered powder deposit can be clearly seen on the left of the three dark scanned sites.

Olakanmi (2013) showed that during laser scanning of the powder bed in SLM, thermal gradients develop which drive the molten metal from the middle to the colder edges, leading to balling up of liquid matter to minimise the surface energy. At the same time, Mumtaz and Hopkinson (2010) found that ionised metal vapour (plasma plume) exerts recoil pressure on the melt pool within a cavity created by evaporation as in Fig. 1A. As investigated by Verhaeghe et al. (2009), this causes the droplets to be expelled upwards away from the melt pool. Hence, the spattering phenomenon is otherwise known as melt expulsion in laser drilling and welding. Qiu et al. (2015) also studied the spattering phenomenon in SLM by both high speed imaging and modelling and concluded that the melt splashing was due to the combination of Marangoni effects at the melt pool surface and below, and also the recoil pressure exerted by metal vapour expansion. In laser welding, Kaplan and Powell (2011) found that the melt pool is also driven by Marangoni convection in the keyhole from the front to the rear. This finding with regards to the location of melt ejection could prove significant in the present study.

Another explanation given by Simonelli et al. (2015) is that as the spattered molten material is ejected, it oxidises during flight in the gas flow. Subsequently, Liu et al. (2015) studied the spatter formation during SLM of SS316L using a high speed camera. It was concluded that higher laser energy input significantly increases spatter behaviour, specifically the spatter size, scattering and jetting height. Droplet spatter was also characterized and found to be three times larger at $119.7 \mu\text{m}$, due to the formation of iron oxides. Energy-Dispersive x-ray Spectroscopy (EDS) mapping done by Simonelli et al. (2015) showed good agreement such that the spattered powders have a spherical morphology and are much larger than the starting powder. Oxides of Mn, Si and Mg with thickness

levels up to a few microns were also discovered on the surfaces of the spattered powder.

Generally, spattering is undesired in laser-based material processing as it affects the properties and appearance of the final work-piece. Since SLM is a powder-bed fusion additive manufacturing process, contamination of the powder bed due to the spattered material affects the melting process. [Liu et al. \(2015\)](#) performed tensile testing using parts manufactured from contaminated powder. Results showed such parts had lower strength due to the higher porosity levels induced by the significantly larger spattered powder. Oxidation effects during SLM also leads to non-uniform part properties. Therefore, minimisation of spattering and its effective removal from the powder bed is critical to ensure the manufacturing of high quality parts.

[Mumtaz and Hopkinson \(2010\)](#) discovered that the use of pulse shaping in SLM reduced spatter ejection during processing. 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. The removal of the spattered powder during SLM is performed by the inert gas flow pumped into the build chamber, which is usually either argon, nitrogen or helium. Besides this, oxidation of the molten powder needs to be minimised as much as possible. Hence, scanning only starts when oxygen content is below 0.1%.

Studies on the influence of the inert gas flow by [Ferrar et al. \(2012\)](#), concluded that flow uniformity is needed to improve the consistency and uniformity of part properties such as compression strength and density. On the other hand, [Zhang et al. \(2013a\)](#) investigated SLM of pure Ti under vacuum (0.0001 bar in reality) using a self developed SLM machine, claimed that gas expansion was removed during scanning of the powder bed. In a separate study, [Zhang et al. \(2013b\)](#) found that the balling phenomenon was also eliminated due to the low temperature and high viscosity of molten pool under low pressure. Unfortunately, the observations of spatter under the pseudo-vacuum conditions were not documented. [Ladewig et al. \(2016\)](#) studied the beam scattering effects by the particles in the gas flow. Laser energy could have been potentially absorbed by the suspended spatter, leading to lower energy input at the powder bed for scanning and thus incomplete melting of the powder bed due to the prior laser-particle interactions.

The effects of the type of inert gas used on the mechanical properties 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 micro-structure. [Dai and Gu \(2015\)](#) performed experiments and simulations to study the effect of the type of gas on metal vaporization behaviour. It was found that argon gas was more effective in achieving a sound surface morphology as compared to nitrogen. Hence, research has shown that the type and quantity of gas chosen is critical in the surface finish of the final part. However, in the above mentioned cases, the role of the direction of gas flow with respect to the scanning 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 spattered powder.

There have also been a considerable amount of research devoted to studying the effect of different scanning strategies for SLM and SLS. For example, [Qian et al. \(2012\)](#) showed that the helix scan strategy lowered the residual stress and deformation in parts and [Stamp et al. \(2009\)](#) achieved porosity control with an alternating orthogonal scan direction for bio-material applications. However, to the best of our knowledge, there has been no investigation so far on the effects of the direction of scanning with respect to the gas flow on the mechanical properties of the fabricated parts. Thus, the primary objective of this study is to investigate how the concurrent laser-spattered powder-gas interactions during SLM would affect the tensile strength of the printed parts.

In this study the effects of these interactions were investigated 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 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 spattered powder 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-spattered powder-gas interactions.

2. Materials and methods

2.1. SLM parameters

A SLM Solutions 280 HL (SLM Solutions Group AG, Germany) machine equipped with a twin (2 x 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. 2A. 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 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 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

2.2. Protocol

For this study, the independent variables “scan direction”, “part location” and “gas velocity” were chosen to investigate how the possible laser-spattered powder-gas interactions during SLM would affect the UTS of the printed parts, see Table 2.

Table 2: 2^3 design experiment

Factor	Low(-)	High(+)
<i>A</i> : Scan Direction	$-x$	$+x$
<i>B</i> : Part Location	left	right
<i>C</i> : 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. 2B. 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. 2A.

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 2: **A:** Layout of part placement. **B:** Local scanning strategy for inner regions in (a) -x (b) +x directions.

The 2^3 factorial design implied 8 experimental conditions, see Table 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: Plus and Minus table for 2^3 design experiment

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

2.3. Experimental observations

2.3.1. Mechanical and chemical analyses of the printed parts

The printed parts were machined according to ASTM E8 Specimen 3 standards (see Fig. 3A), and subjected to tensile strength tests using the Instron

Figure 3: **A:** Sample of machined tensile specimen. **B:** Camera set-up placed outside SLM Solutions 280 HL build chamber observation window (computer not seen in image)

5569 tensile tester. A 50kN load was used along with a strain rate of 0.25 mm/mm/min.

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.

2.3.2. Spattered powder

The powder that was deposited near the outlet (more precisely, in the yellow-marked region (254 x 48 mm) in Fig. 2A) 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 spattered powder 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 spattered powder at that area are: (i) it is not possible to collect the spattered powder 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.

2.3.3. High-speed camera observation

To observe the spattering process and laser-spattered powder-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. 3B).

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, 1975).

2.4. Statistical analysis

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 spattered powder 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 spattered powder. All statistical calculations were done using the Minitab software.

3. Results

3.1. Tensile strength

The average and standard deviation of the UTS for each run are shown in Fig. 4A. 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.

The effects of the main factors are illustrated in Fig. 4B. 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 4. For main factors A and C , $F_0 > F_{0.01,1,16}$ at a value of 8.531, as tabulated in Table 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 strength significantly.

Figure 4: **A**: Mean UTS (MPa) and $\pm$ standard deviation in each run. **B**: Main effects plot for UTS (MPa).

Table 4: ANOVA for the 2^3 design experiment (UTS)

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

3.2. SEM-EDS

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

Figure 5: SEM images of **A**: Fresh powder; **B**: Spattered powder collected near the outlet observed; **C**: Single particle of spattered powder. **D**: Sample EDS result of single spattered powder.

Table 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

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. 6. It can be observed that more pores and unmelted powder were seen for run *b* in Fig. 6B.

Figure 6: 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. Quantity of spattered powder collected near the outlet

From Fig. 7A, 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 spattered powder took place for the opposite configuration at run *b*.

Figure 7: **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. 7B 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 spattered powder are tabulated in table 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 spattered powder since $F_0 > F_{0.01,1,112}$ at a value of 6.8667.

Table 6: ANOVA for the 2^3 design experiment (spattered powder)

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

3.4. Visual observation of laser-spattered powder-gas interactions

To study the laser-spattered powder-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. 8A 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. 8B, 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.

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.

4.1. Effect of gas flow velocity on part quality

The results in Section 3.1 showed that the higher the gas flow velocity, the better the part quality. This effect is most likely mediated by the spattered powder gas with higher velocity can carry more spattered powder to the outlet, leaving less spattered powder on the powder bed, which in turn results in better part quality. Section 3.3 showed that higher gas velocity indeed implied significantly more powder deposited near the outlet, contributing less to the

Figure 8: Images extracted from video at intervals of $24 \mu\text{s}$. **A**: Run *c*. **B**: Run *ac*.

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 spattered powder and maintaining the fresh powder on the powder bed.

Next, little has been reported regarding the effect of spattered powder 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 with the fresh powder on the powder bed, the lower the part quality. Fig. 6B 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 3.2 showed through SEM analyses that the spattered powder 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 spattered powder as reported by Liu et al. (2015). To validate the difference in porosity as in Fig. 6, the density of the 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.

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 3.1), 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. 9.

During laser scanning, when the gas flow carries the spattered powder to the outlet, a fraction of the spattered powder 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. 9A), the spattered powder is more likely to be blown into the path of the beam as compared to scanning against the flow (Fig. 9B), because of the location of melt ejection with respect to the movement of the laser beam. The results in Section 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 spattered powder burnt by the laser). This finding is further reinforced by the snapshots in Fig. 8: scanning in the direction of the flow was associated with larger “sparks” above the powder bed, which in turn hint at more spattered powder burnt by the laser beam. To further validate the difference in the amount of sparks produced, image processing of the snapshots in Fig. 8 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 9: Schematic of laser beam scanning. **A**: scanning in the same direction as the flow. **B**: scanning against the direction of the flow, which might have caused more spattered powder.

Next, as scanning in the direction of the flow generates more burning of the spattered powder, 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).

4.3. Spattered Powder Accumulation

As established, scanning against the flow and at higher gas velocity, led to both higher UTS and accumulated spattered powder. To show the relationship between these two outcomes, the results were normalised and compared on the same plot. From Fig. 10, it can be seen that generally, the two bars follow the same trend throughout the runs, except for the case of run *ac*, where the normalised UTS value is lower than that of the spattered powder.

Figure 10: Normalised plots for spattered powder and UTS

In general, as more spattered powder accumulates near the outlet, less of it gets burned by the laser beam as explained earlier, serving as an indication of the part quality.

4.4. Other parameters that can influence part quality and spattering

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 to 190 MPa when subjected to solution treatment. This was due to the reduction in solid solution strengthening when the trapped 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-spattered powder-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.

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 spattered powder near the chamber outlet, regardless of the gas velocity and part placement. It was observed that scanning in this direction generally produced more finer particles and sparks as the spattered powder 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 greater 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.

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