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<th>Spattering in selective laser melting: a review of spatter formation, effects and countermeasures</th>
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ABSTRACT: Spattering is an unpreventable and largely undesired phenomenon in selective laser melting (SLM). The ejected particles from the melt pool would often deposit on the powder bed when not effectively removed by the shielding inert gas flow, leading to contamination and subsequently parts to be printed with lower quality. In this paper, the formation, effects and countermeasures with regards to spattering in SLM are reviewed.

KEYWORDS: SLM, spatter, contamination, oxidation, gas flow, Additive Manufacturing

INTRODUCTION

Background of Selective Laser Melting

In recent years, Additive Manufacturing (AM) has been gaining significant attention due to the unlimited possibilities in terms of producing complicated and customised parts to be used as prototypes or even applied in the real world. Applications in the automotive and aerospace sectors often demand metal parts of superior mechanical properties such as high tensile strength, fatigue, density and toughness. Therefore, Selective Laser Melting (SLM) has emerged as a practical and viable solution to satisfy these demands.

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 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.
Formation and characteristics of spattering

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 Figure 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 multiphysics 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.

However, more recent experimental evidence from the use of high speed cameras with a frame rate of 100 kfps have revealed a more dominant cause of spatter generation. In the work conducted by Ly et al. (2017) on the SLM of stainless steel 316 L 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 6 to 20 m/s and form 60% of all spatter generated.

The studies performed by Ly et al. (2017) is further validated by Bidare et al. (2018) 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. (2017) characterised the spatter of aluminium alloy AlSi10Mg by varying the laser power and speed. It was

![Figure 1. Schematic of spatter ejection from melt pool and its transport by the inert gas flow.](image-url)
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, D. Wang et al. (2017) 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. Scanning Electron Microscopy (SEM) 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.

Effects of spattering

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 require 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 from 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 and 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.
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. X. 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 and 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 vapor material, and more importantly, the accumulation of spatter.
On the other hand, Zhang et al. (2013) 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 and 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.

CONCLUSION

In this paper, the formation, effects and countermeasures with regards to the spattering phenomenon in SLM have been reviewed. While much research has provided insights into the formation and effects of spatter particles, studies on the effectiveness of the inert gas flow in transporting such contaminants have been more limited. Therefore, future innovations for the removal of spatter particles during SLM need to be devised in order to achieve a contaminant free powder bed suitable for the manufacturing of large scale parts.

REFERENCES


