Effect of gaseous environment on powder particle spattering during laser powder bed fusion process

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Laser Powder Bed Fusion (LPBF) is an advanced additive manufacturing technique, which uses a high-power laser to selectively melt and fuse metal powder particles to create complex geometries. However, the component quality is significantly affected by the spatter during the LPBF process. These spatters can significantly affect the quality and consistency of the final product by introducing defects and irregularities. The velocity, flow direction, and quantity of the sputtered powder particles are influenced not only by laser power and scan speed but also by the gaseous environments during the LPBF process. This research investigates the impact of various gaseous atmospheres, specifically argon, nitrogen, and oxygen, on the dynamics of powder spattering. It combines experimental observations with high-speed imaging and numerical simulations to analyze the trajectory, velocity, and distribution of ejected particles under different gas environments. The results indicate that the type of gas plays a crucial role in the spattering mechanism, with each gas influencing the molten pool dynamics and particle ejection in unique ways. For example, argon and nitrogen exhibited more controlled ejection patterns but caused larger melt pool perturbations due to their higher densities. It provides valuable insights for optimizing LPBF processes by selecting appropriate gaseous environments, thereby enhancing build quality and reducing defects. The study concludes that a tailored approach to gas selection can effectively mitigate spattering effects and improve the overall efficiency and reliability of LPBF additive manufacturing. By understanding and controlling the influence of different gases, it can achieve more consistent and higher-quality production outcomes in additive manufacturing.

1. Introduction (Times New Roman 10pt)

Laser Powder Bed Fusion (LPBF) has become a crucial technology in additive manufacturing, enabling the production of complex metal components with high precision. By selectively melting and fusing metallic powder particles layer by layer, LPBF offers unparalleled design flexibility and material efficiency. However, a significant challenge in this process is the occurrence of powder spattering, where molten particles are ejected from the melt pool during laser scanning. These spatters can degrade the quality of the final product by introducing defects such as porosity and surface irregularities, which can compromise the structural integrity of the manufactured part.

The behavior of spatter in LPBF is influenced by several factors, including but not limited to the laser power, scan speed, and the properties of the powder material [1]. Among these, the gaseous environment within the build chamber plays a critical role, yet it has been relatively underexplored in existing research. The type of gas used, such as argon, nitrogen, or oxygen, interacts differently with the molten metal due to variations in density and thermal conductivity. These differences can significantly affect the dynamics of the melt pool and the subsequent ejection and dispersion of particles [2], leading to variations in the spattering behavior and, consequently, the quality of the final build.

This study aims to investigate the effects of different gaseous environments on powder spattering during the LPBF process. By integrating experimental observations with high-speed imaging and numerical simulations, the research examines how argon, nitrogen, and oxygen influence the trajectory, velocity, and distribution of ejected particles. The insights gained from this study will contribute to optimizing LPBF processes by allowing for the selection of the most suitable gas environment to minimize spattering and improve the overall quality and reliability of additive manufacturing outputs.

2. Experimental setup

Figure 1(a) shows the in-situ observation method. A continuous fiber laser (redPOWER R4 CW, wavelength: 1070 nm, SPI Lasers, Inc.) was used to irradiate the metal powder (PSS316L, Sanyo Special Steel Co.) layer surface to observe the molten pool and spatter. The powder, with a thickness of 50 µm, was layered on a SUS316L metal plate. The continuous oscillation laser had a focused beam diameter of 150 µm, and the output power was varied between 50 and 200 W.

Real-time observation was conducted using a pulsed laser irradiation system (CAVILUX HF, Cavitar Ltd.) with a wavelength of 640 nm, and a high-speed camera (Hyper Vision HPV-X, Shimadzu Corp.) was employed for real-time observation. Filters were used to suppress scattered and plume light from the continuous wave laser when the sample stage moved. The frame rate of the high-speed camera was 20,000 fps, with an exposure time of 0.3 μs. A bandpass filter was utilized to filter out light wavelengths around 640 nm.

The laser scan speed varied from 10 to 1000 mm/s, located on a move stage. This stage was placed in a sealed box made of acrylic plates with a thickness of 3 mm. Four types of gas, Helium (He), Argon (Ar), Nitrogen (N_2), and Oxygen (O_2), were introduced into the sealed box. The oxygen content was controlled at around 2% (He, Ar, N_2) and 99% (O_2). Considering that the laser passes through the acrylic, which has a transmission property of around 90% at the wavelength of 1070 nm [3], the laser power was increased by a factor of 1.11 during the experiment.

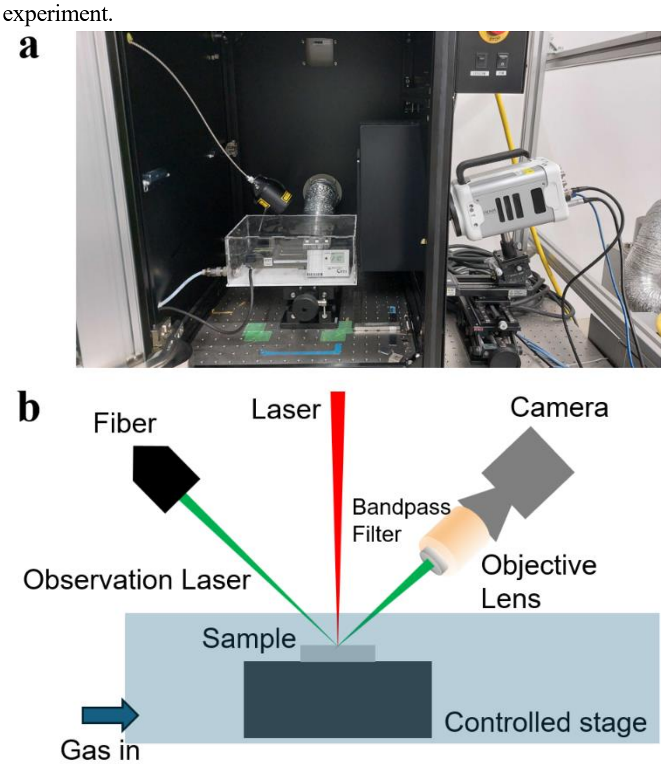

Fig. 1 Schematic of (a) experimental setup and (b) observation system

3. Results and Discussion

The spattering of powder particle is significantly influenced by the laser scan speed. Figure 2 illustrates the spattering of particles at a laser power of 100 W, with scan speeds varying from 10 to 1000 mm/s in an atmospheric environment. At the high scan speed of 1000 mm/s, large droplets are formed in the air, aligning themselves in a straight line at an angle of approximately 30° to the horizontal plane. Additionally, the distance of the laser-melted area on the sample surface is shorter than the laser scan distance of 5 mm. This occurs because, at high scan speeds, the energy density is low, insufficient to melt the powder layer at the beginning of the laser scan.

As the scan speed decreases, the spattering behavior changes. At 500 mm/s, large droplets no longer form a straight line, and in contrast to the behavior at 1000 mm/s, many small particles are generated and distributed irregularly. Meanwhile, some large bubbles remain on the surface of the powder bed, unable to float in the air, eventually condensing into large particles on the powder bed's surface. When the scan speed is between 50 and 200 mm/s, the particles spatter irregularly, and the melted width increases as the scan speed decreases. Furthermore, particle spattering nearly disappears when the scan speed is reduced to 10 mm/s. This can be explained by the longer contact time between the laser and the material at low scan speeds, which leads to energy accumulation and higher temperatures, thereby fully melting the gold powder bed. Under the influence of the Marangoni effect, as the temperature increases, the surface tension decreases, which effectively balances energy and material distribution in the molten pool, thereby reducing spattering.

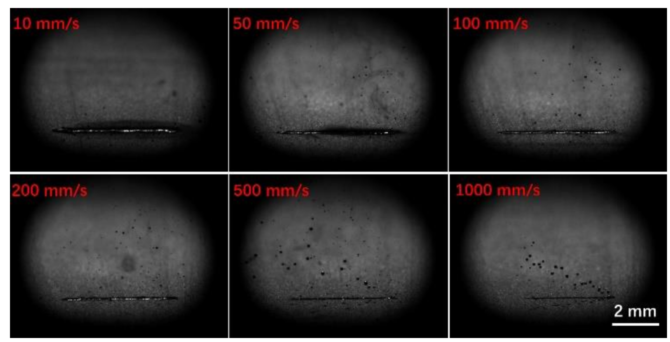

Fig. 2 Spatter of powder particles at a power of 100 W with different scanning speeds in the atmospheric environment

Compared to the atmospheric environment, spattering during the LPBF process differs significantly in various gaseous environments, as shown in Figure 3. In the N_2 environment, the number and size of droplets decrease, and the particle spattering becomes more chaotic. Some droplets remain on the powder bed surface and form large spherical particles after cooling. In contrast, due to the low density and high diffusivity of He, the gas flow is less turbulent [4]. This steady flow results in fewer random disturbances, leading to more regular particle spattering. The rapid cooling in a helium environment causes the sputtered particles to be smaller and denser. Since the gas exerts less force on the particles, they spatter over a shorter distance and exhibit less disorder.

However, in the O_2 environment, droplets oxidize in the oxygen, forming a large plume. Due to the higher density of Ar, the molten pool surface may experience more gas resistance, causing some of the molten metal to be squeezed out to form sputtering particles. Additionally, in the Ar environment, the enhanced evaporation of materials results in the formation of high-pressure metal vapor above the molten pool, which in turn pushes the molten metal to eject, significantly enhancing particle sputtering behavior. The number and energy of sputtered particles increase, their flight distance is longer, and their distribution range is wider.

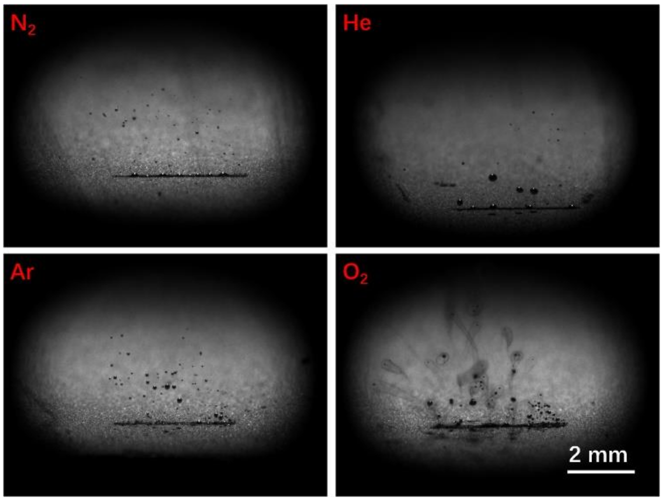

Fig. 3 Spatter of powder particles at a power of 200 W and scanning speed of 1000 mm/s in different gaseous environment

4. Conclusions

This study demonstrates that the gaseous environment within the LPBF chamber significantly influences powder spattering behavior. Helium, with its low density and high diffusivity, results in more stable and controlled spattering, while nitrogen and argon lead to more irregular spattering due to their higher densities. Oxygen promotes oxidation, creating large plumes and increasing the amount of spatter. Additionally, laser scan speed plays a crucial role, with lower speeds reducing spattering by allowing more energy to accumulate, leading to more complete melting of the powder bed.

Optimizing both the gaseous environment and laser scan speed can effectively minimize spattering, thereby improving the structural integrity and surface quality of LPBF-manufactured parts. These findings provide valuable guidelines for enhancing the reliability and quality of components produced through additive manufacturing.

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