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Experimental investigation of melt pool behaviour during selective laser melting by high speed imaging

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ABSTRACT

Melt pool behaviour and the characteristics of the surrounding metal powder during selective laser melting (SLM) are captured using high-speed imaging, and the influence of the substrate temperature and the line building sequence on the formation of the built structure and the generation of spatter particles is experimentally investigated. The results indicate that the substrate temperature has a measurable effect on the formation of droplets and the generation of spatter particles, while the volume specific energy density of the process was the principal factor affecting the built structure.

1. Introduction

Additive manufacturing (AM), such as selective laser melting (SLM) using metals, is currently one of the most promising techniques for producing 3D printed structures, particularly because it possesses tremendous potential for producing complex, lightweight, and functionally optimized parts [1]. Many industries, especially the medical, aerospace, and automotive industries, are expected to benefit from the ability of AM to produce high quality models at reduced manufacturing costs and lead times. The primary advantages of AM include the flexibility of the process and the wide variety of metal materials that are available for use [2].

Despite these advantages over traditional manufacturing methods, several deficiencies still remain in AM processes. Particularly in SLM processes, the various process parameters that govern everything, from the geometry of the design created using three-dimensional CAD to its subsequent construction with heated metal powder, must be considered in order to build a high quality part. The quantity of process parameters involved makes it difficult to determine the optimal conditions. The generation of spatter particles also affects the quality of the built structure, even when appropriately accounting for the process parameters. Most spatter particles have been observed to either contaminate the powder bed surface or fall onto the built structure, thus promoting metallurgical defects [3]. Therefore, the behaviour of spatter particles and the physics underlying their generation must be understood to improve and stabilize the SLM process. The visualization of the SLM process by high-speed imaging has been shown to be an effective method for clarifying the physical phenomena associated with SLM. King et al. [4] observed the key-hole formation inside the melt pool and calculated the key-hole threshold by considering the depth variation and the normalized enthalpy value. Matthews et al. [5] focused on the denuding of metal powders from the substrate surface near the built structure, and showed that the gas flow induced by the vaporization of the melted powder was the dominant driving force of this denuding. Wang et al. [6] observed the generation of spatter particles during the SLM process and concluded that the input energy at least partially dictated the quantity and type of spatter particles, categorizing them into three particle types: droplets, metallic jets, and non-melted powders. Additionally, Khairallah et al. [7] simulated the melt flow during the SLM process to clarify the effects of the recoil pressure and Marangoni convection, and suggested that the vaporization of the melt pool was a key factor in the generation of spatter particles and denuding of metal powder from the substrate.

The present work focuses on the behaviour of the melt pool during the SLM process using metals to gain a thorough understanding of the phenomena that occur during the melting and solidification of the metal powder. In particular, the substrate temperature is understood to play an important role in the SLM process as it affects the formation of porosities and cracks inside the built structure [8]. In this experimental study, melt pool behaviour and disposition of the surrounding metal powder are captured using high-speed imaging, and the influence of substrate temperature on the building quality of the melted powder is investigated. The influence of the sequence of line building on the formation of the melt pool and the generation of spatter particles is also observed.

2. Experimental setup and powder characteristics

A schematic of the experimental setup is shown in Fig. 1 and the experimental conditions are summarized in Table 1. The equipment consisted of a self-designed SLM system composed of a laser oscillation device, a high-speed digital imaging apparatus, and a

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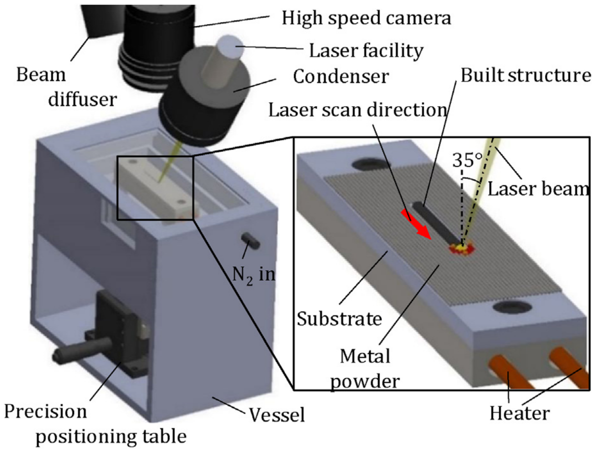

Fig. 1. Experimental setup for the capture of melt pool behaviour.

Table 1
Experimental conditions.

Laser source		
Wavelength	[nm]	1,070
Power	[W]	300
Beam diameter at focal spot	[μm]	80
Scan speed	[mm/s]	50–200
Substrate		
Material		Carbon steel
Thickness	[mm]	5
Surface roughness R_a	[μm]	3.5
Temperature	[°C]	25–200
Metal powder		
Material		Fe, Ni, Co, Mo
Shape		Irregular
Average diameter	[μm]	25
Layer thickness	[mm]	0.05
High-speed video camera		
Recording speed	[fps]	10,000
Resolution		384 × 228
Light source		Metal halide lamp

powder building platform. The platform was set on a precision position table (Nippon Thompson Co., Ltd.: CTLH220H-3030A/Y0035) and covered by an acrylic vessel so that it could be filled with nitrogen to prevent oxidization while building the metal powder. The platform was capable of maintaining a temperature of up to 200 °C through the insertion of a cartridge heater. The substrate upon which the metal powder was placed was constructed of carbon steel (AISI 1049), and its surface was sandblasted by white alumina (WA) abrasive grains to provide a constant roughness of $R_a = 3.5$ μm.

Maraging steel with an average particle size of 25 μm was used as the metal powder, and was deposited on the substrate by gravitational force and flattened using a levelling blade. The thickness of the metal powder bed was maintained at a constant 50 μm for the duration of the experiment. A continuous wave ytterbium fibre laser (IPG Photonics Corp.: YLR-300-AC-11) was then focused onto the powder bed surface by a condenser with a focal length of 150 mm. The relative intensity of the laser beam formed a Gaussian shape, and the laser beam then irradiated the powder bed surface at an angle of 35°, as shown in Fig. 1. The resulting elliptical beam dimensions on the powder bed surface were approximately 80 × 98 μm.

When the laser beam was scanned over the powder bed surface, the melted area on the deposited powder was captured using a high-speed camera (nac Image Technology Inc.: MEMRECAM Q1v) positioned vertically above the metal powder bed, with a recording speed of 10,000 fps (max. 100,000 fps). An optical filter was used to protect the imaging sensor from the scattered laser beam. The influence of the process parameters on the structure building was determined using these captured images and the volume specific energy density (VSED), which was calculated using the process parameters of the laser power, laser scan speed, beam diameter, and layer thickness. The influence of the substrate temperature and the surrounding metal powder on the melt pool behaviour was also evaluated. Additionally, the first and subsequent line building were compared in order to clarify the solidification behaviour of the melted powder and the generation of spatter particles. Spatter particles ejected from the melt pool that collected on the loose powder surface were counted from the high-speed camera images, then collected and observed using a scanning electron microscope (SEM) (JEOL Ltd.: VSM-6290LVU).

3. Results and discussion

3.1. Observation of laser irradiated area in first line building

Fig. 2 shows a typical high-speed camera image taken around the laser irradiated area, along with a schematic representation. In the case pictured, the substrate temperature was 25 °C and the VSED was 1500 J/mm^3. When the laser beam was used to heat the metal powder, the powder formed a melt pool in the laser irradiated area due to the sharp temperature rise induced by the laser beam scan. Spatter particles and metallic jets were also observed around the melt pool. The size of the melt pool was substantially larger than the beam diameter cast onto the powder bed surface. The melted powder then solidified after the laser beam passed through the melted area.

This solidified area was characterized by two regions: a built area and a denuded area. The denuded area was formed around the built structure via the cohesion of the melted powder to the melt pool. However, some metal powder particles located far from the melt pool were also melted by the heat of the laser beam, remaining in the locations at which they were initially generated in the denuded area as droplets that were not agglutinated into the melt pool. Notably, the formation of droplets cannot be attributed to the spatter particles ejected from the melt pool. These results suggest that the formation of droplets is related to the wetting properties of the substrate surface. The laser beam used in this study forms a Gaussian shape, so the energy applied to the powder surface severely decreases as the distance from the centre of the laser irradiated area increases.

It is well known that the melted powder forms a ball shape when a low VSED is provided on the powder surface [9]. The formation of droplets on the denuded area was observed to coincide well with this “balling” phenomena in previous work. In addition, the shape of the droplets was observed to be spherical due to the tendency of the surface tension to minimize the surface area, creating liquid spheres. The height-to-diameter aspect ratio of the droplets was 0.86, which was obtained by measuring the diameter in the captured images and the height with the surface profiling system (Tokyo Seimitsu Co., Ltd.: SURFCOM 2000DX). Therefore, the formation of droplets could not be attributed to the melting of the substrate. These results indicate that the threshold for the cohesion of the melted powder to the melt pool is determined by its distance from the laser irradiated area, and that the wettability of the substrate is related to the agglutination of the droplets around the melt pool. The melt pool is widely understood to be formed by many complicated physical phenomena, such as laser and powder interactions, heat and mass transfer, fluid flow, and melting and solidification [7]. In this research, the wettability of the substrate surface was also found to be one of the essential parameters related to the formation of the melt pool.

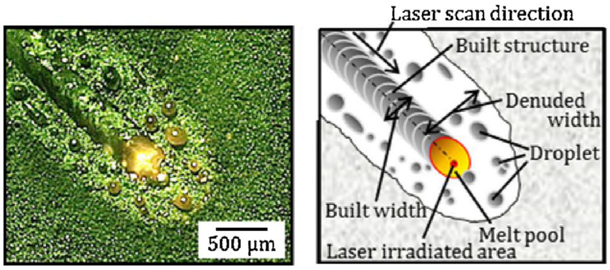

Fig. 2. Image of laser irradiated area after first line building.

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