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On the measurement of relative powder-bed compaction density in powder-bed additive manufacturing processes

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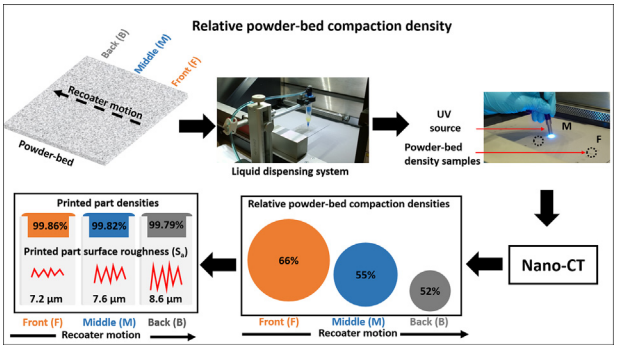
HIGHLIGHTS

- A process-independent relative powder-bed compaction density measurement technique is presented and applied to laser powder-bed fusion.
- Ultraviolet curable polymer is used to bind powder particles, followed by nano-computing tomography scanning on the bonded particles.
- Results show variation in the relative powder-bed compaction density across the build bed and printed part properties.

GRAPHICAL ABSTRACT



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ABSTRACT

Experimental studies in the literature have identified the powder-bed compaction density as an important parameter, governing the quality of additively manufactured parts. For example, in laser powder-bed fusion (LPBF), the powder-bed compaction density directly affects the effective powder thermal conductivity and consequently the temperature distribution in melt pool. In this study, this physical parameter in a LPBF build compartment is measured using a new methodology. A UV curable polymer is used to bind powder-bed particles at various locations on the powder-bed compartment when Hastelloy X was used. The samples are then scanned using a nano-computing tomography (CT) system at high resolution to obtain an estimation of the relative powder-bed compaction density. It is concluded that due to the interaction between the recoater and the variation in the powder volume accumulated ahead of the recoater across the build compartment, the relative powder-bed compaction density decreases along the recoater moving direction (from 66.4% to 52.4%.). This variation in the powder-bed compaction density affects the density and surface roughness of the final printed parts that is also investigated. Results show that the part density and surface quality decrease ~0.25% and ~20%, respectively, along the build bed in direction of the recoater motion.

1. Introduction

Additive manufacturing (AM) has gained a new momentum in many industrial sectors [1, 2]. AM processes are becoming more common in the product development lifecycle because of their remarkable capabilities of manufacturing complex geometries compared to

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conventional manufacturing methods. For instance, manufacturing of complex shapes and consolidation of assemblies are now feasible without the use of multiple manufacturing steps, thus saving time and resources [3]. One of the disadvantages of AM techniques, however, is the cost of raw materials and low repeatability [4].

There are various powder-bed AM processes that are classified based on the powder joining mechanisms. The most common methods of joining powder particles in powder-bed systems are the deployment of thermal energy generated by the irradiation of laser, electron beam, and plasma, or the use of binders [5–7]. In the binder jetting 3D printing process, powder particles are adhered to each other using a liquid-based binder that is jetted through a printhead at selected locations within each layer [5]. Electron beam and laser processes adhere the powder particles by melting or sintering. Laser powder-bed based AM processes are commonly known as Laser Beam Melting (LBM), Selective Laser Melting (SLM), Laser Powder-bed Fusion (LPBF) [2].

Laser powder-bed fusion (LPBF) is categorized as one of the main metal AM processes based on ASTM standard ISO/ASTM 52900 [8]. The LPBF process consists of a series of steps for manufacturing complex parts by typically using a high intensity laser as an energy source to melt and fuse selective regions of powder, layer-by-layer, to build the final shape [9]. Similar to other AM processes, LPBF includes various process parameters. The most common process parameters studied in the literature include laser power, scanning speed, hatch spacing, layer thickness etc. [10, 11] that need to be optimized for achieving high quality parts [12]. In addition to the above mentioned laser process parameters, one of such parameters, which can significantly affect the final product properties (e.g., density, surface roughness) is the powder-bed compaction density in the build compartment [13, 14]. In general, the successful industry adoption of metal AM relies on understanding the complex interactions between the design, the used materials, and the process to ensure high product quality and reliability. These relationships are typically developed using costly empirical approaches. To enable a lean manufacturing approach, simulations, monitoring and process control of LPBF are becoming a high interest research and development area [15].

In order to effectively simulate the complex laser-material interaction occurring during the LPBF process, the relative values for powder compaction density in the powder-bed are required [16–18]. For example, Denlinger et al. [19] used volume of voids between particles as input to their simulations to calculate thermal history. Other researchers used various types of functions to relate the bulk and powder densities of materials [16, 17]. Powder-scale simulations, such as Discrete Element Method (DEM), do not consider the powder-bed compaction density as they can directly account for the powder distribution and packing in the powder-bed [20]. Due to the lack of information in the literature on the exact values for the powder-bed compaction density, this process property is assumed a fixed number across the bed, where in many cases the chosen values are approximated [16, 18]. Therefore, it is important to develop a systematic approach for the measurement of powder-bed compaction density as this parameter directly governs the final part quality and the simulated behavior of the laser-material interaction [21].

There are various methods presented in the literature to quantify the powder-bed compaction density during AM processes. Liu et al. [14] investigated the effect of powder-bed compaction density on the final part properties by printing a 30 × 30 × 30 mm container during the AM process and weighing the powder inside. They concluded that a wider range of particle size distribution provides higher powder-bed compaction density and results in parts with high density and surface quality. Jacob et al. [13] conducted an experimental study to measure the powder-bed density. They used a custom container (closed hollow cylinder with a conical lid), which captured the loose powder inside the container during the process from various locations on the build plate. Karapatis et al. [22] studied the powder-bed compaction density across the build compartment using a similar technique and have also discussed 'wall effects' on the powder-bed density due to the presence of container. Similarly, Elliott et al. [5] studied the effect of powder particle size and distribution on powder-bed compaction density during binder-jet AM. They suggested that the particle size distribution with a median particle size (D50) closer to 25 μm is an ideal size for high powder-bed density. However, they did not investigate the reason or effect of differences in powder-bed densities on AM-made parts. Most of the powder-bed density measuring techniques discussed involve using containers/vessels and are therefore process dependant. Due to the interaction between the powder recoating mechanism and the build bed during the manufacturing process, the powder density may be significantly affected by the design of the powder capture artefacts. In addition, the evaluation of the internal volume of these powder capture vessels and the volume of captive particles in them results in a high level of uncertainty in estimating the powder-bed density.

The discussion presented shows the direct correlation between powder-bed compaction density and the particle size distribution. In addition, various studies show the effect of powder distribution on the final part quality [6]. Experimental work by McGeary [23] illustrates the effect of powder size distribution on the powder-bed densities. Spierings et al. [24] have used 316 L stainless steel powders with D50 of 15 μm and 28 μm to produce parts with higher density than steel powders with D50 of 38 μm. There have been many studies on the effect of particle size distribution on the sintering process of metals and ceramics (e.g. [25, 26]).

The literature lacks comprehensive studies on accurate measurement of powder-bed compaction density and its cause and effect on AM-made parts. To the best knowledge of authors, there are no studies in the literature, which focus on process-independent methods to measure the powder-bed compaction density. The aim of this paper is twofold. Firstly, a new method to measure the relative powder-bed compaction density is proposed by encapsulating particle samples through highly precise injection of a UV- curable low-viscous polymer at select locations in the build bed, followed by density measurement of the samples using 3D nano-CT. Secondly, the effect of relative compaction density on the final part quality is investigated. In this regard, density and surface roughness are measured in the AM-made parts printed on different locations of the build bed. Results show differences in the density and roughness of AM-made parts thus highlighting the importance of powder-bed compaction density.

2. Experimental procedures

2.1. Powder material characterization

Commercially available Hastelloy X powder from EOS GmbH (EOS NickelAlloy HX, Krailling, Germany) with a D10 (diameter at 10% cumulative volume), D50 (median diameter) and D90 (diameter at 90% cumulative volume) of 15 μm, 30 μm and 46 μm respectively was used in this study. An average material composition for each element of Hastelloy X alloy provided by EOS® is given in Table 1.

An EOS M290 (EOS GmbH, Krailling, Germany) was used for the LPBF process and relative powder-bed compaction density measurements. Parts were printed with laser power of 220 W and speed of 1000 mm/s with a layer thickness of 60 μm. All other parameters such as scanning strategies, core and skin parameters, etc. were kept as default for all parts.

A dynamic optical particle analyzer (Retsch Camsizer X2, Retsch Technology GmbH, Haan, Germany) was used to measure the powder size distribution from various locations on the build bed. Surface roughness measurements of metal LPBF samples were taken with a high performance confocal laser scanning microscope (Keyence VK-X250, Keyence Corporation, Osaka, Japan). Density measurements of the LPBF samples (ρ_P) were taken using a temperature corrected Archimedes water displacement method using the equation:

$$\rho_P = \frac{W_D \rho_w}{W_D - W_W} \quad (1)$$