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Full Length Article

Critical evaluation of the pulsed selective laser melting process when fabricating Ti64 parts using a range of particle size distributions

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ABSTRACT

Selective Laser Melting (SLM) is a metal additive manufacturing process where parts are fabricated from metal powder based on CAD data. Selection of the best process parameters for the pulsed SLM processes is a fundamental problem due to the increased number of parameters that have a direct impact on the melt pool compared to the continuous SLM processes. In previous studies, volumetric energy density or scan speed have been used as control variables for applied energy. In this paper, the process parameters (laser power, exposure time, point distance and hatching distance) were considered individually, in addition to particle size distribution and layer thickness. The Taguchi experimental design method was used to determine and optimise the effect of the selected input parameters. The effect of exposure time and its correlation with layer thickness and particle size distribution was then investigated. The results show the best combination of process parameters which can provide fully or near fully dense parts. The results also show the minimum exposure time that can be used with different powder types and layer thicknesses. The paper concludes with a study which shows the part location has a significant impact on sample quality.

1. Introduction

Powder bed metal additive manufacturing (PB-MAM) processes such as selective laser melting (SLM) and selective laser sintering (SLS) are used to fabricate metal parts directly from metal powder by adding layers of powder. There are three main steps in PB-MAM: (1) spreading the powder as a layer, (2) selectively melting the powder according to a CAD file and (3) lowering the platform. These steps are repeated until the part is completely built. A range of systems have been classified under the technologies of energy source, fabrication process, and the form of raw materials as described in the work of Frazier [1], Gu et al. [2] and Herderick [3].

In powder-based metal additive manufacturing systems, powder characteristics are critical because they affect the process efficiency and the quality of built parts, therefore it is essential that process parameters are selected accordingly. The spherical shape of powder particles (powder particle morphology) and proper particle size distribution facilitate good packing density and contribute to fabricating parts with good mechanical properties. Large amounts of fine particles will affect the flowability of powder which may lead to an inconsistent powder layer. Insufficient powder can cause voids between powder particles resulting in poor density and uneven surface roughness. The percentage of fine particles to coarser grains should be considered to minimise voids and produce fully or near fully dense parts [4].

A number of previous studies have investigated the influence of the laser power source on part density. Demir et al. [5], when using a pulsed wave SLM system to build 18Ni300 maraging steel, found that with a fixed energy density, exposure time plays a major role in improving part density by increasing the average power. However, the dimensional accuracy was found to be negatively affected by the increased exposure time. Pulsed SLM systems give more flexibility to control the volumetric energy density for denser and higher hardness compared to continuous wave SLM systems as it was shown with Al-12Si alloys [6]. Moreover, pulsed-SLM systems improved the surface roughness and are suitable for lattice structures and thin walls [5,7]. Even though the pulsed laser systems deliver lower average power than continuous systems, they result in stronger sintering connection between grains [8].

Volumetric energy density (VED) is the amount of energy applied to a unit volume of powder. However, variation in part densities may be caused by the combination of parameters that deliver

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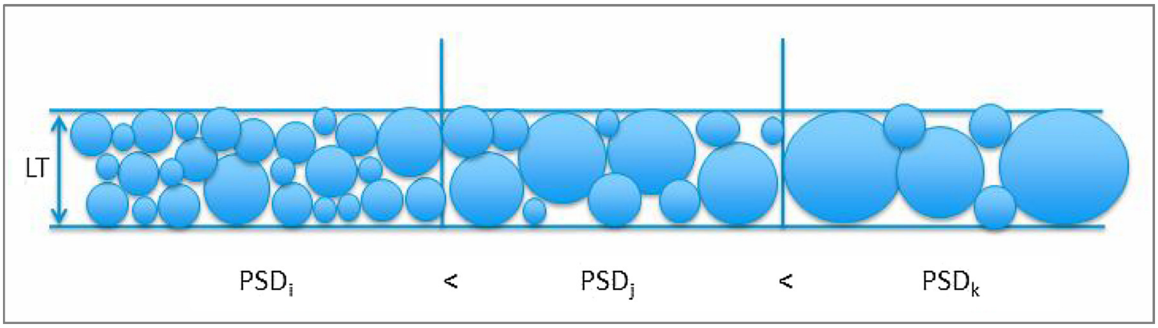

Fig. 1. Different particle size distributions (PSD) vs. fixed layer thickness (LT).

the VED. For instance, using a hatching distance of 100 μm with a scan speed of 50 mm/s gives the same VED as using a hatching distance of 50 μm and a scan speed of 100 mm/s but the resulting part density is different. When the hatching distance is large, there will be no overlap between adjacent lines. The melt pool size increases when the laser power is high and scan speed is slow. If the distance between scan lines is larger than the melt pool size, voids (unmolten powder) will be created [9,10]. The relationship between part density and VED is not linear, and there are ranges of process parameters that can be used to fabricate near full density parts. This means that the value of VED should not be used as an appropriate indicator of melt energy for obtaining parts with defined density.

Process parameters are not the only factors that affect the quality of SLM parts. Powder properties such as particle size distribution (PSD) also influence the density of the part produced at a certain VED. Simchi [11] found that for a given layer thickness, using a smaller particle size distribution gives increased density until a specific point is reached. However, they showed that below this point, using smaller powder particle can negatively affect the density. This could be due to the amount of powder vs layer thickness. Heat transfer from the top layer to the bottom is affected by the number and size of the gaps between the particles, together with the thermal conductivity of powder. Fig. 1 illustrates the potential differences between the amount and the size of gaps for different particle size distributions for a given layer thickness. Therefore, it is possible that insufficient melt energy reaches the bottom of the layer leaving un-melted powder [12]. Additionally, smaller particles sizes have a greater potential to be disturbed by the high energy of the laser, therefore creating voids in the distributed layer.

The effect of particle size distribution (PSD) on the SLM process and on the fabricated parts has been studied for 316L [13,14] and Ti64 [15]. The results of these studies can be summarised as follows: metallic powder that has a small PSD (more fine particles [13]) tends to have denser powder bed and higher thermal conductivity. These two characteristics help to fabricate parts with higher density, smoother surfaces and higher mechanical strength compared to parts fabricated by coarse/large particles powder. However, a large proportion of fine particles may lock together causing poor flow. On the other hand, powder with large PSD has better flowability and parts that are fabricated by larger particle size have higher elongation.

Spierings and Levy [4] found that the actual layer thickness is different to the theoretical layer thickness and can be described as the effective layer thickness (LT_{eff}). The effective layer thickness can be calculated according to the density of layer thickness using the following equation, Eq. (1):

$$Effective\ Layer\ Thickness\ \left(LT_{eff}\right) = \frac{D_m}{D_p} * (LT) \quad (1)$$

Table 1
Particle size distributions and density of all powder types: T1, T2 and T3.

	Ti64 Powder Type		
	T1	T2	T3
D10 (μm)	20.6	43.2	51.7
D50 (μm)	32	59.3	73.6
D90 (μm)	48.6	81.2	105
Powder Density (g/cm^3)	4.42	4.41	4.41
Apparent Density (g/cm^3)	2.58	2.60	2.50
Tapped Density (g/cm^3)	2.86	2.85	2.78

Where; D_m is the density after melting, D_p is the density of the powder layer and LT is the theoretical layer thickness. Therefore, the actual layer thickness that is affected by melting energy is the effective layer thickness which should be considered when selecting the process parameters.

A review of previous work suggests that little work has been carried out on the correlation of particle size and layer thickness and their effect on the density of fabricated parts, specifically for pulsed SLM systems. This work addresses this gap in existing knowledge and aims to determine the influence of changing powder size and layer thickness for the same volumetric energy density which is controlled by exposure time.

2. Materials and methods

The study carried out comprised two main phases. The first phase comprised a process parameter optimisation. A single powder type was used for optimisation to find the most influential parameters and determine the best combination to achieve the highest part density. The design and analysis of experiments were carried out using the Taguchi experimental design method. In the second phase, three types of powder with different particle size distributions (PSD) were used to investigate the effect of PSD and layer thickness on part density where other process parameters were fixed at their optimum values.

2.1. Materials selection and processing conditions

Three types of Titanium alloy Ti6Al4V ELI powder with different particle size distributions (PSD) were used in this research. The powders are gas-atomised and are spherical in their nature. Their particle size distributions and density are shown in Table 1.

Table 2 shows the nominal chemical analysis which reveals low oxygen content (approximately 0.1 wt%). The laser melting machine is an AM250 model, manufactured by Renishaw in the UK, and equipped with a 200W modulated fibre laser which generates a pulsed laser wave. The laser beam has a minimum nominal diameter of 70 μm and wavelength of 1070 nm. The machine has a build volume of 250 mm x 250 mm x 300 mm. The spot size of the beam was kept at its minimum value for all builds for providing the high-