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A STUDY ON THE INFLUENCE OF POWDER PACKING DENSITY ON
THE MELT TRACK IN THE SELECTIVE LASER MELTING PROCESS

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ABSTRACT: A numerical model was employed to mimic the selective laser melting (SLM) process. The powder bed following Gaussian distribution was generated by using the discrete element method (DEM). Different packing densities of the powder bed were generated by applying a compression force along the build direction. The melt track characteristics were simulated using a computational fluids dynamics (CFD) model. An average powder diameter of 27 μm and a layer thickness of 50 μm were used in this model. The study found that the powder packing density significantly affects the melt track characteristics. Increase in the packing density leads to an increase in the melt track height while reducing the melt track depth and melt track width.

KEYWORDS: Additive manufacturing, selective laser melting, computational fluid dynamics, packing density, single melt track.

INTRODUCTION

SLM is a powder bed-based additive manufacturing (AM) process and is considered as one of the most popular AM technology adopted by various industries [1, 2]. It is able to produce complex geometry with different types of materials such as metals, ceramics, and composites [1, 3]. SLM is capable of building parts with a density of 99.88% [4]. Furthermore, SLM is reported to produce parts with superior mechanical properties [5]. For example, it was reported that Nano-TiB2 decorated AlSi10Mg composite (NTD-Al) fabricated by SLM process achieved very high ultimate tensile strength of around 530 MPa, excellent ductility at 15.5% and high micro-hardness of about 191 HV0.3, which were higher than most conventionally fabricated Aluminium alloys.

Nowadays, besides conducting fabrication experiments, quality control techniques such as non-destructive testing (NDT) and in-situ monitoring are employed to improve the fabrication quality [6, 7]. However, both experiments and quality control techniques are expensive and time consuming, thereby limiting the applications in AM fields. Therefore, many researchers had developed computational models for the SLM process. Ganeriwala and Zohdi generated a DEM model to simulate the heat transfer in the powder bed [8]. The influence of laser intensity profile on the melt track during the SLM process was also modelled and studied [9]. In SLM fabrication, input parameters such as laser power, scanning speed, layer thickness, melting and solidification process play an important role on the mechanical properties of the printed part [3, 10].
In this study, an attempt is made to study the influence of the packing density on the melt track by using numerical modelling. The simulation model is employed to mimic the deposition of powder, melting and solidification process of 316L stainless steel powder during SLM process.

POWDER BED GENERATION

Method
DEM is commonly employed to model the powder bed in SLM process [11, 12]. In this work, the packing information of powder particles was achieved by using LIGGGHTS® [13]. The powders are considered as solid spheres with their radii following a Gaussian distribution. Gravitational and contact forces are exerted on each particle, and the motions of particles are calculated based on Newton’s second law. The details of equations and parameters used in this simulation can be found in ref [14].

Powder bed generation
In this simulation, powder beds of 50 μm layer thickness but different packing densities were generated through the following steps. Firstly, 1500 particles were dropped freely due to the gravitational force along y-axis to form a free surface in a simulation domain of $x \times y \times z = 1500 \times 800 \times 300 \, \mu m^3$. Secondly, a blade, which describes the horizontal force of the roller, is employed to generate powder beds with different thicknesses of 50 μm (Bed A), 55 μm (Bed B) and 60 μm (Bed C). In order to create different packing densities, we compressed Bed B and Bed C to the same 50 μm layer thickness. As a result, these three powder beds, though exhibit similar layer thickness at 50 μm, their packing densities are different as illustrated in Figure. 1.

![Figure 1. Powder beds with Gaussian distribution of powder (a) viewed from the front with a recoater to form a layer thickness of 50 μm, and viewed from the side of (b) Bed A, (c) Bed B, and (d) Bed C. A compression force is applied to Bed B and Bed C to form a layer thickness of 50 μm.](image)

The packing density was calculated in the domain $x \times y \times z = 1000 \times 50 \times 300 \, \mu m^3$ where the CFD model is performed. The packing density of the powder beds are listed in the Table 1. Bed A has lowest packing density while Bed C has the highest. Before applying the compression force, Bed C has layer thickness of 60 μm – the highest value among three samples. Therefore, the total volume of particles in Bed C is largest. As a result, it leads to the higher packing density of Bed C than the other two samples.
Table 1: Packing density of the powder bed model (%)

<table>
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<th>Packing density (%)</th>
<th>Bed A</th>
<th>Bed B</th>
<th>Bed C</th>
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<tbody>
<tr>
<td>Before compression</td>
<td>38.73</td>
<td>44.07</td>
<td>47.32</td>
</tr>
<tr>
<td>After compression</td>
<td>38.73</td>
<td>52.50</td>
<td>61.44</td>
</tr>
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</table>

MELT TRACK SIMULATION

Methodology
A CFD model, using Open Field Operation and Manipulation (OpenFOAM®) [15], was developed to mimic the heat transfer and melt flow process in the SLM process. The equations of conservation of mass, momentum, and energy were solved in this model. The numerical model accounts for the interfacial forces including surface tension, Marangoni force and recoil pressure. In the SLM process, the recoil pressure plays a role in penetrating the molten material and forming the keyhole. The surface tension force tends to minimize the surface area of the molten materials. The Marangoni force is used to simulate the change of surface tension due to temperature gradient [16]. In this simulation, the laser beam intensity profile assumes a Gaussian distribution and the laser heat flux can be described as $q_{laser} = \frac{2\eta P_{laser}}{r^2} \exp\left(-\frac{2w^2}{r^2}\right)$, where $P_{laser}$ is the laser power, $r$ is the beam spot radius, $w$ is the distance from the calculation cell to the beam centre, and $\eta$ is the absorptivity coefficient [17]. Heat conduction and heat loss, including the evaporation loss, convection and radiation, are represented in the model. Details of the terms which are not explained here could be found in refs [11, 16].

CFD simulation setup
The three-dimensional (3D) computational domain had a dimension of $x \times y \times z = 1000 \times 300 \times 300 \ \mu$m$^3$ as described in Figure. 2, in which the gravitational force is along the $y$-direction. The simulation domain is to mimic the SLM process as close as possible. In the model, the substrate is 200 $\mu$m in height, the layer of powder is 50 $\mu$m thick, and the layer of air is 50 $\mu$m high. A constant mesh grid size of $4 \times 4 \times 4 \ \mu$m$^3$ was used in this study. The initial temperature of the domain was set as room temperature at 300 K.
Figure 2. CFD simulation domain with $x \times y \times z = 1000 \times 300 \times 300 \, \mu m^3$ with 200 $\mu m$ thickness of substrate, 50 $\mu m$ thickness of powder, and a layer of air on top.

A laser power of 175 W and scanning speed of 0.55 m/s were adopted to model the SLM process. The laser Gaussian beam with focusing diameter of 80 $\mu m$ was considered as the heat source. The top surface of the powder bed absorbs the heat energy with an absorption coefficient of 0.4. The thermo-physical properties of 316L stainless steel can be determined by $\Phi = a + bT + cT^2$ [18, 19], where $\Phi$ is the material property, $T$ is temperature, and $a$, $b$, and $c$ are constant coefficients. The thermal material properties such as density of solid metal, density of liquid metal, melting temperature, boiling temperature and other parameters can be found in refs [18, 19].

DISCUSSIONS

The laser beam is considered as a heat source moving from right to the left along $x$-direction, and the laser power is absorbed by the top surface of the powder bed. Due to the applied heat source, metal powders near the laser spot are heated up and started to coalesce together when they reach the melting point, giving rise to the formation of a melt track. When the temperature of the surface near the laser spot approaches the boiling point, a keyhole is formed because of the recoil vapor pressure which has discussed in previous studies [9, 11]. Figures. 3(a) to 3(c) illustrate the melt pool geometries of three samples at the cross-section of $x = 500 \, \mu m$. It shows obviously that the Bed A sample gives a larger and deeper melt pool compared to the other two samples.

![Figure 3](image)

Figure 3. Cross-section views at $x = 500 \, \mu m$ at $t = 1400 \, \mu s$ of (a) Bed A, (b) Bed B, and (c) Bed C. The white contour line encompasses the area of the deepest melt pool formed at (a) $t = 670 \, \mu s$, (b) $t = 680 \, \mu s$, and (c) $t = 670 \, \mu s$.

The melt pool depths, widths and the melt track heights are investigated in this study. The melt pool depth is measured from the top surface of the substrate to the bottom of the melt pool, and the width of the melt pool is taken where its width is the largest. The melt track height is measured as the height of the melt track where the reference plane, which has the melt pool height of zero, is taken as the top surface of the substrate. The melt pool geometries are measured at different cross-sections of $x = 400 \, \mu m$, $x = 500 \, \mu m$, and $x = 600 \, \mu m$, and the average values are used to compare between three samples. The details of the melt pool parameters are listed in Table 2. The results show that the melt pool depth of the Bed A is deeper than the one of Bed B, and the melt pool of
Bed C is shallowest. Due to the increased packing density from Bed A to Bed C, the required energy to melt the powder layer of Bed C is highest. With the same energy intensity to scan these three models, the melt pool depth of Bed C is hence shallowest. Since deeper melt pool will form a larger melt pool width, therefore, the melt pool width decreases from Bed A to Bed C. Moreover, a larger packing density of the powder bed could form a higher melt track height. As a result, the melt track height of Bed C is the highest, and it is lowest in Bed A.

Table 2: The average melt pool depths, widths, and melt track heights at the cross-sections of \( x = 400 \mu m, x = 500 \mu m, \) and \( x = 600 \mu m \) of different powder bed

<table>
<thead>
<tr>
<th>Melt track parameters</th>
<th>Bed A</th>
<th>Bed B</th>
<th>Bed C</th>
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<tbody>
<tr>
<td>Depth (( \mu m ))</td>
<td>65.33</td>
<td>57.33</td>
<td>54.00</td>
</tr>
<tr>
<td>Width (( \mu m ))</td>
<td>115.33</td>
<td>112.00</td>
<td>99.33</td>
</tr>
<tr>
<td>Height (( \mu m ))</td>
<td>20.67</td>
<td>28.67</td>
<td>34.00</td>
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The melt pool geometry is greatly affected by the packing density of the powder bed. There is a need to consider the relationship between the melt pool depths/widths and the melt track heights. In each layer, higher packing density gives a higher melt track, but a shallower and narrower melt pool. It will lead to lack of fusion between tracks and layers. On the contrary, a lower packing density leads to lower melt track height, albeit with larger melt pool depth and width. It means the adherence between adjacent tracks and layers will be enhanced, however, the build rate might be decreased due to the low melt track height.

CONCLUSION

In this work, a numerical model was employed to study the effects of packing density of the powder bed on the melt track geometry. Different packing densities of the powder beds were generated by using a compression force along build direction. The study shows that higher packing density of the powder bed leads to higher melt track, but at the same time a shallower and narrower melt pool. On the contrary, the powder bed with lower packing density will have deeper and wider melt pool, while the melt track height is lower.

REFERENCES


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