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A study on the influence of scanning strategies on the levelness of the melt track in selective laser melting process of stainless steel powder

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ABSTRACT

By using a numerical model for selective laser melting (SLM) process, this study investigates the melt pool behaviours and the resulting defects due to different scanning strategies. Two common scanning patterns were tested: sequential and boustrophedon. The study found that sequential scanning strategy leads to non-flat printed surface, while the boustrophedon strategy produces flat printed surface. At the beginning of the tracks, the molten material is pulled from the hot laser spot to the cold tail by the Marangoni force leading to an increase in the melt pool height of the sequential and alternated strategies. On the other hand, due to the deep keyhole and the high cooling rate when the laser is switched off, a recess is formed at the end of the tracks. Similar phenomenon can be observed in the boustrophedon scanning strategy at the start and ending of the track.

1. INTRODUCTION

Of the various additive manufacturing (AM) technologies, laser powder-bed fusion is probably the most common process for direct metal fabrication. Selective laser melting (SLM), being a promising laser powder bed fusion process, has been widely used to fabricate both metallic and ceramic parts [1-3]. It enables the creation of parts with complex geometries and high density, while matching the mechanical properties of parts conventionally manufactured [4]. The SLM process uses a high intensity laser source to create a melt

pool from the powder bed. This results in a complex thermal history that influences the microstructure, material properties, residual stress, geometrical accuracy and distortion of the final part.

Previous experimental studies suggested that the processing conditions, such as laser parameters and powder properties, greatly affect the quality of SLM fabricated parts. Gan and Wong established the process conditions and characterized the resulting properties of spodumene produced by SLM [3]. The study found that the porosity of spodumene is affected by the layer thickness and other factors. Do et al. [5] studied the effects of the laser energy density on densities and surface roughness of Ti-6Al-4V samples processed by SLM. They found that high laser energy density may lead to low surface quality while a low laser energy density tends to produce high percentage of porosity. Apart from the above, Thijs et al. conducted experimental study on the scanning strategy effects on the microstructure, texture and the porosity in the parts [6]. To achieve functional parts meeting the quality standards, suitable processing parameters for SLM fabrication are typically chosen by trial and error experiments, which could be time consuming and expensive. In addition, quality control techniques such as non-destructive testing (NDT) and in-situ monitoring open up possibilities to improve the fabrication quality [7, 8]. Unfortunately, high costs limit their widespread applications in AM fields. Accordingly, many researchers have resorted to using simulation techniques to gain deep insights into the physical mechanisms underlying the complex phenomena during SLM process, such as the melt pool dynamics, thermal evolution, growth of microstructure, etc. Finite element method was employed to model the melt-pool geometry of the SLM process [9]. It was observed that the rate of change in the width of the melt pool by altering the laser scanning speed is different from that of the depth. Körner et al. [10] developed a numerical tool based on 2D lattice Boltzmann method (LBM) to predict local powder melting and re-solidification processes of the powder. The model is able to mimic physical mechanisms such as wetting or capillary forces.

The multi-track mechanisms have been studied experimentally and through simulation previously [11, 12]. However, the influence of the scanning strategies on the melt pool dynamics has not been insufficiently understandable. In this work, an attempt is made to study the influence of the scanning strategies on the melt pool dynamics by using computational fluid dynamics (CFD) to mimic the melting and

solidification process of 316L stainless steel powder during SLM. The aims of this work are to observe the levelness of printed surface based on different scanning strategies.

2. COMPUTATIONAL MODEL

In this work, pure 316L stainless steel substrate and spherical powders were used in the simulations. The powders have a mean diameter of 27 μm with a full width at half maximum of 10 μm . The packing density of the powder bed was about 35%. The numerical model was divided into two parts: discrete element method (DEM) and computation fluid dynamics (CFD).

2.1. DEM simulation of powder bed

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 normal distribution. Gravitational and contact forces are exerted on each particle, and the motions of particles are calculated based on Newton's second law.

The powder bed was generated through the following steps. Firstly, a cloud of powders was generated randomly and dropped freely to form a deposited powder bed. A blade, which was defined in the model, moved across the powder bed to generate a uniform layer thickness of 50 μm with top free surface.

2.2. Melt flow simulation

A CFD model, using Open Field Operation and Manipulation (OpenFOAM®) [14], was developed to mimic the heat transfer and melt flow process in SLM. Interfacial forces including surface tension, drag force via Darcy's term, Marangoni force, and recoil pressure were considered in the simulation of the melt pool dynamics. Heat conduction and heat loss, including the evaporation loss, convection and radiation, are

represented in the model. In the SLM process, the recoil pressure plays a role in penetrating the molten material and forming the keyhole. Since the keyhole formed in the SLM process is usually not as excessively deep as in welding, laser reflection is omitted in the simulation [15]. In this work, a heat flux following the Gaussian distribution and with constant absorptivity was imposed on the top free surface to model the laser input.

The volume of fluid (VOF) method was adopted to capture the free surface (gas-metal interface) [2]. In the model, α_1 represents the volume fraction of metal, and $(1 - \alpha_1)$ represents the volume fraction of gas. Accordingly, $\alpha_1 = 0$ describes that the grid cell is entirely gaseous, while $\alpha_1 = 1$ represents that the cell is entirely metallic. Additionally, the metal phase undergoes phase transformation (solid to liquid, or liquid to solid) during the SLM process. Therefore, a linear function gamma, γ_l , was computed to represent the melting and solidification state [16]. $\gamma_l = 1$ symbolizes that the cell is fully melted when the temperature is above the liquidus temperature, while $\gamma_l = 0$ indicates that the cell is in the solid phase when the temperature is below the solidus temperature. Any value between 0 and 1 means that the material is undergoing melting in the cell. Therefore, the volume fraction of solid material is $\alpha_1(1 - \gamma_l)$ and volume fraction of liquid metal is $f_L = \alpha_1\gamma_l$. Each parameter is defined via a weight function, $\bar{x}$, calculated as $\bar{x} = x_s\alpha_1(1 - \gamma_l) + x_l\alpha_1\gamma_l + x_g(1 - \alpha_1)$, where x_s , x_l , x_g are the value of parameter x in solid, liquid and gaseous phase respectively.

The numerical model solves the conservation equations of mass, momentum, and energy [2]. The model assumed molten material is incompressible, so the continuity condition is defined as

$$\nabla \cdot \mathbf{u} = 0, \quad (1)$$

where $\mathbf{u}$ is the velocity of molten material.

In order to predict the kinetics of the melt pool, all interfacial forces appearing in SLM process are included in the momentum equation, and is computed as

$$\begin{aligned} \frac{\partial \bar{\rho} \mathbf{u}}{\partial t} + \nabla \cdot (\bar{\rho} \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) - K_C \left[\frac{(1-f_L)^2}{f_L^3 + C_K} \right] \mathbf{u} + \bar{\rho} \mathbf{g} \\ + \left[\sigma \hat{\mathbf{n}} + \frac{d\sigma}{dT} (\nabla T - \hat{\mathbf{n}}(\hat{\mathbf{n}} \cdot \nabla T)) + \hat{\mathbf{n}}(p_v \cdot \hat{\mathbf{n}}) \right] \|\nabla \alpha_1\| \left[\frac{2\bar{\rho}}{\rho_s \alpha_1 (1-\gamma_l) + \rho_l \alpha_1 \gamma_l + \rho_g} \right] \end{aligned} \quad (2)$$

where t is the time, p is the pressure, μ is the dynamic viscosity, $\bar{\rho}$ is the density, $\mathbf{g}$ is gravitational acceleration, and T is the temperature. Details of these terms could be found in the ref [11].

The energy conservation is expressed as

$$\begin{aligned} \frac{\partial \bar{\rho} \bar{C}_p T}{\partial t} + \nabla \cdot (\bar{\rho} \bar{C}_p T \mathbf{u}) = -\frac{\partial \bar{\rho} \Delta H_f}{\partial t} - \nabla \cdot (\bar{\rho} \mathbf{u} \Delta H_f) + \nabla \cdot (\bar{k} \nabla T) - \\ q_{loss} \|\nabla \alpha_1\| \left[\frac{2\bar{C}_p \bar{\rho}}{C_{ps} \rho_s \alpha_1 (1-\gamma_l) + C_{pl} \rho_l \alpha_1 \gamma_l + C_{pg} \rho_g} \right] + q_{laser} \end{aligned} \quad (3)$$

where C_p is the heat capacity, ΔH_f is the enthalpy change due to fusion, and k is the thermal conductivity.

The heat loss at the metal/gas interface is described by $q_{loss} = q_{convloss} + q_{emisloss} + q_{evaploss}$ [11, 17]. Details of the terms which are not explained here could be found in refs [2, 11].

2.3. Simulation parameters

The three-dimensional (3D) computational domain had a dimension of $x \times y \times z = 1000 \times 300 \times 600 \mu\text{m}^3$ as depicted in Fig. 1, where gravitational force is along the y -axis. The domain consisted of a $200 \mu\text{m}$ tall substrate, a $50 \mu\text{m}$ tall powder layer, and a $50 \mu\text{m}$ tall air layer above the powder bed. The model contains 2.8 million elements with constant mesh grid size of $4 \times 4 \times 4 \mu\text{m}^3$. The initial temperature of the domain was set as 300 K.

Laser parameters for CFD simulation is listed in Table 1. The material used in this work is 316L stainless steel, and its thermo-physical properties can be determined by $\Phi = a + bT + cT^2$ [18, 19], where Φ is the material property, T is temperature, and a , b , and c are constant coefficients, which are listed in Table 2. The viscosity coefficient of the liquid metal phase is calculated as $\mu = 10^{(2358.2/T - 3.5958)}$ Pas [19].

3. RESULTS AND DISCUSSION

3.1. Levelness of single-track

The single-track simulation is conducted in order to test the levelness of the single melt track. The laser beam is considered as a volumetric heat source moving from right to the left (see Fig. 2), and the laser power is absorbed by the top surface of the powder bed. Metal powders near the laser spot are heated up and when they reached the melting point, they start to coalesce giving rise to the formation of a melt track. When the temperature of the surface near the laser spot approaches the boiling point, the recoil pressure overcomes the surface tension force, and a keyhole is formed as shown in Fig. 2(a). Right after the laser beam moved away to the next position (or switched off), the keyhole collapsed as the surface tension force surpasses the recoil pressure. Fig. 2(b) depicts that the melt track is higher at the beginning of the scanning but becomes lower at the end of the scanning. The results agree with the previous simulation and experimental studies [2, 11, 20]. At the beginning of the scan track, surface tension force will pull the molten material from the hot laser spot towards the cooler region due to the Marangoni effect leading to increased track height. On the other hand, the melt track height is lower at the end. It is because a deep keyhole is formed due to the recoil pressure, and the surface tension force is only able to partially fill up the keyhole. Moreover, due to the rapid solidification, a recess is formed.

3.2. Levelness of multiple melt track

Multi-track simulations were performed using sequential and boustrophedon scanning strategies as illustrated in Fig. 3. Sequential scanning represents unidirectional scan from right to the left with constant hatch spacing of $h = 100 \mu\text{m}$ (Fig. 3(a)). In the boustrophedon strategy, the laser beam moves continuously

from right to the left and from the left to the right with a constant hatch spacing of $h = 100 \mu\text{m}$ (Fig. 3(b)). Due to the limitation of the computational resources, simulation work was only conducted for three tracks. Nonetheless, it is sufficient to study the melt pool geometry and the levelness of the melt track.

The melt track height is measured as the average height of the melt track at different cross-sections where the reference plane, which has the melt pool height of zero, is taken as the top surface of the substrate. The melt track heights of the first, second, and third tracks of the sequential and boustrophedon scanning strategies are plotted in Fig. 4. For sequential tracks, the melt pool heights are highest at the beginning and decrease towards the end of the track, as shown in Fig. 4(a). As explained in section 3.1, such nonuniformity is caused by the surface tension force, recoil pressure and rapid solidification. Since unidirectional scanning is employed in the sequential strategy, all the single tracks exhibit higher heights at the beginning and lower at the end of the tracks. As a result, the sequential scanning pattern forms non-flat printed surfaces with the highest at the beginning and the lowest at the end of printed surface. In contrast, the boustrophedon strategy produces a flatter printed surface as shown in Fig. 4(b). As the laser beam moves continuously from right to the left and from the left to the right, the molten material flows continuously from the n^{th} track to the $(n-1)^{\text{th}}$ track (see Fig. 5). Since the molten material flows continuously from the beginning of the n^{th} track to the end of the $(n-1)^{\text{th}}$ track, the fluid flow is able to fill up the recess. As a result, the boustrophedon method is able to produce a flatter printed surface. However, the melt track is highest at the beginning of the first track and lowest at the end of the last track due to the same reason explained in section 3.1.

4. CONCLUSIONS

This paper investigates the melt pool behaviour due to different scanning strategies. Two common scanning strategies have been tested and they are the sequential and boustrophedon scanning patterns. The simulation results prove that sequential scanning strategy lead to non-flat printed surface – highest at the beginning and lowest at the end of the track. Boustrophedon strategy, on the contrary, is able to produce flat printed surface.

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Fig. Captions List

- Fig. 1 Simulation domain with $x \times y \times z = 1000 \times 300 \times 600 \mu\text{m}^3$. The model comprises $200 \mu\text{m}$ thickness of substrate, $50 \mu\text{m}$ thickness of powder, and a layer of air on top. The mesh grid size is $4 \times 4 \times 4 \mu\text{m}^3$.
- Fig. 2 Temperature distribution of single scanning track at cross-section $z = 130 \mu\text{m}$ at (a) $t = 1300 \mu\text{s}$ (b) $t = 1500 \mu\text{s}$. The white contour line encompasses the area where the temperature is above the liquidus temperature. After the laser beam is switched off for $200 \mu\text{s}$ ($t = 1500 \mu\text{s}$), a recess can be observed at the end of the track.
- Fig. 3 Two scanning strategies namely, (a) sequential and (b) boustrophedon, with (i) represents schematic of the scanning pattern and (ii) depicts the top view of the fused zone, and $h = 100 \mu\text{m}$ is the hatch spacing.
- Fig. 4 Melt track height of the first, second, and third track of (a) sequential, (b) boustrophedon scanning strategies at different cross-sections along x -direction.
- Fig. 5 Cross-section view at $x = 864 \mu\text{m}$ of the boustrophedon strategy at $t = 1320 \mu\text{s}$ showing the temperature distribution and the molten metal of the melt pool from the second track flowing to the first track. The white contour line encompasses the area where the temperature is above the liquidus temperature.

Table Caption List

Table 1	Input data for CFD simulation
Table 2	Thermo-physical properties for 316L stainless steel

Table 1: Input data for CFD simulation

Parameters	Value
Power, P	175 W
Scan velocity, v	0.55 m/s
Hatch spacing, h	100 μm
Radius of laser beam, r	0.04 mm
Absorption coefficient, η	0.4

Table 2: Thermo-physical properties for 316L stainless steel

Material properties, Φ	Coefficients		
	a	b	c
Density of solid metal (kg/m ³)	8084	-0.4209	-3.89×10^{-5}
Density of liquid metal (kg/m ³)	7433	0.0393	-1.8×10^{-4}
Boiling temperature (K)	3090	0	0
Solidus temperature (K)	1658	0	0
Liquidus temperature (K)	1723	0	0
Molar mass (g/mol)	55.93	0	0
Specific heat of solid metal (Jkg ⁻¹ K ⁻¹)	462	0.134	0
Specific heat of liquid metal (Jkg ⁻¹ K ⁻¹)	775	0	0
Specific heat of gas (Jkg ⁻¹ K ⁻¹)	1000	0	0
Thermal conductivity of solid metal (Wm ⁻¹ K ⁻¹)	9.248	0.01571	0
Thermal conductivity of liquid metal (Wm ⁻¹ K ⁻¹)	12.41	0.003279	0
Thermal conductivity of gas (Wm ⁻¹ K ⁻¹)	0.02	0	0
Surface tension (Nm ⁻¹)	3.282	0	0
Temperature coefficient of surface tension (Nm ⁻¹ K ⁻¹)	-8.9×10^{-4}	0	0
Effective enthalpy of metal vapor (Jkg ⁻¹)	7.45×10^6		

Atmosphere pressure (Nm^{-2})	101000
Universal gas constant ($\text{JK}^{-1}\text{mol}^{-1}$)	8.314
Stefan-Boltzmann's constant ($\text{Wm}^{-2}\text{K}^{-4}$)	5.67×10^{-8}
Emissivity coefficient	0.24

Fig 1: Simulation domain with $x \times y \times z = 1000 \times 300 \times 600 \mu\text{m}^3$. The model comprises 200 μm thickness of substrate, 50 μm thickness of powder, and a layer of air on top. The mesh grid size is $4 \times 4 \times 4 \mu\text{m}^3$.

Fig 2: Temperature distribution of single scanning track at cross-section $z = 130 \mu\text{m}$ at (a) $t = 1300 \mu\text{s}$ (b) $t = 1500 \mu\text{s}$. The white contour line encompasses the area where the temperature is above the liquidus temperature. After the laser beam is switched off for $200 \mu\text{s}$ ($t = 1500 \mu\text{s}$), a recess can be observed at the end of the track.

Fig 3: Two scanning strategies namely, (a) sequential and (b) boustrophedon, with (i) represents schematic of the scanning pattern and (ii) depicts the top view of the fused zone, and $h = 100 \mu\text{m}$ is the hatch spacing.

Fig 4: Melt track height of the first, second, and third track of (a) sequential, (b) boustrophedon scanning strategies at different cross-sections along x -direction.

Fig 5: Cross-section view at $x = 864 \mu\text{m}$ of the boustrophedon strategy at $t = 1320 \mu\text{s}$ showing the temperature distribution and the molten metal of the melt pool from the second track flowing to the first track. The white contour line encompasses the area where the temperature is above the liquidus temperature.