Research article

Influence of the thermal-fluid behavior on the microstructure evolution during the process of selective laser melting of Ti6Al4V

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A R T I C L E   I N F O

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A B S T R A C T

To account for the microstructure evolution corresponding to the changed scanning speed, the thermal-fluid dynamic model of the meltpool during the selective laser melting (SLM) process of Ti6Al4V was established by numerical method to study the thermal characteristics and the melt flow behavior. Results showed that increasing the laser scanning speed would result in a lower peak temperature but a higher heating and cooling rate on the specimen. Both the meltpool size and its duration were reduced with the increased laser scanning velocity. Typically, a waved solid/liquid interface was observed at the bottom of the rear part of the meltpool as the time elapsed, especially for a larger scanning velocity. The melt flow velocity had a magnitude of hundreds of millimeters per second and showed almost a linear decrease with the increased scanning speed. Except for the change in cooling rate, the variation in flow velocities of the liquid metal consequent to different laser scanning speeds may be another possible reason for the observed microstructure change. The final result suggests that the scanning velocity must be carefully tailored to obtain the optimized combination of process parameters for industrial application, allowing for its adverse influence on the microstructure morphology and thermal stress/deformation caused by higher values.

1. Introduction

Ti6Al4V is widely used in the field of aerospace industry because of its excellent properties such as light weight, high fracture toughness and corrosion resistance, etc. It is an essential material for the manufacturing of aircraft fuselage structures, wing parts and aero-engine parts. Selective laser melting (SLM) process, also known as the laser powder bed fusion (LPBF) given by the International Organization of Standardization (ISO), in which the powder bed is selectively melted layer by layer using the heat source of high energy laser beams, is an efficient technique for the direct printing of complex structures due to its high manufacturing precision [1]. It has demonstrated promising potential for creating aerospace components with complex configurations using precious materials [2]. Although there have been many reports on SLM of titanium alloy, metallurgical defects and internal stress control are still the bottleneck problems that have long restricted the development of laser additive manufacturing technology for metal components [3]. Because of the complex multi-physics, non-equilibrium metallurgical phenomena under the interaction between the laser beam and metal powders, defects such as porosity, tensile residual stress, cracks, and distortion are likely to occur in the fabricated parts if the process parameters are not properly designed [4, 5, 6, 7].

Scholars have carried out many research works on different processes and materials to improve the mechanical performance of metal parts prepared by laser additive manufacturing. In addition to controlling the processing parameters of the manufacturing process and improving the property of metal powders, more and more researchers are seeking to improve the quality of laser processed parts by means of exerting an external excitation, e.g., an electromagnetic field [8, 9], ultrasonic field [10, 11], and high-frequency micro-vibration [12], etc. The electromagnetic field is introduced mainly to regulate and control the flow characteristics of liquid metal in the meltpool. It has been suggested that different fluid flow characteristics have major implications for not only the density of the prepared material but also the columnar/equiaxed crystal transformation and the final grain size [13, 14, 15]. Therefore, it is necessary to study the melt flow characteristics in the unsteady metallurgical process of SLM for a comprehensive understanding of the improved mechanical property by optimizing process parameters. Since the flow characteristics are strongly dependent on the process parameters, and the meltpool stands very short time, it is generally challenging...
to obtain the accurate flow field information in the meltpool by experimental tests. At present, the characteristics of metallurgical hydrodynamics are frequently studied via numerical analysis methods instead of experimental tests.

Gu et al. studied the meltpool evolution and track morphology during SLM of multiple materials via an integrated model based on the discrete element method (DEM) and computational fluid dynamics (CFD), found that the phase migration at the interface is related to the convection flow inside the meltpool, which also contributes to the mixing of the two materials and elemental diffusion [16]. The same method is employed by Lee et al. to model the heat transfer, fluid flow and solidification microstructure of Inconel 718 alloy fabricated by laser powder bed fusion [17]. Based on the calculated temperature gradient $G$ and solidification rate $R$, they found that the solidification morphology is dominated by fine dendritic microstructure with some cellular, and they suggested that the fine dendritic microstructure is formed due to the high values of both $G$ and $R$ in the meltpool. Li et al. studied the surface-tension-driven flow by the CFD model and predicted the microstructure based on the calculation of solidification parameters for laser linear welding of 304 stainless steel [18]. They found that the microstructure morphology changed from equiaxed dendrites to fine columnar dendrites to coarse columnar dendrites, and the grain size increased from the top to the bottom of the meltpool because the interface stability factor was larger at the bottom and the cooling rate was larger at the top section. Based on a 3D finite element model considering Marangoni convection and laser optical penetration, Zhang et al. investigated the thermofluid field in the meltpool and its influence on the shape and dimensions of the meltpool during SLM of Inconel 718 alloy [19]. They suggest that the Marangoni effect driven by surface tension during the SLM process makes the fluid flow state in the meltpool an outward convection. Panwisawas et al. studied the evolution of pores during SLM of Ti6Al4V by thermal fluid dynamics and experimental observation, found the morphology of pores changed from near-spherical to elongated shape as the laser scan speed increased, which can be ascribed to the change of flow pattern in the melt pool obtained by CFD models [20]. Moreover, they suggest that the Marangoni force and recoil pressure are among the main driving forces for the instability of melt flow during SLM, which is responsible for the increased porosity and surface roughness [21]. Based on the open-source CFD code OpenFOAM, Cao studied the pore evolution at mesoscopic scale during SLM of 316L stainless steel powder and proposed that the pore defect under higher volumetric energy density is attributed to the “keyhole” effect, which makes the entrained gas could not escape in time [22].

Mostly, present studies use the temperature gradient and solidification rate derived from fluid simulation to disclose the influence of process parameters on the solidified microstructure consequent to the laser additive manufacturing process. However, fewer studies have related the flow velocities under different process parameters to the evolution of the material’s microstructure. It has been suggested that the magnitude of fluid velocity in the meltpool varies significantly for different materials and process parameters.

Cui et al. studied the effect of Marangoni convection on the thermal and fluid behavior of meltpool based on a 3D transient melting-solidification model for laser cladding process of TiB/TiC4 metal matrix composites, found the most considerable velocity, about 0.23 m/s, appears on the surface of the meltpool away from the center [23]. Manvatkar et al. developed a 3D heat transfer and material flow model to simulate the temperature and velocity fields in a laser-assisted layer by layer deposition process [24]. They found the velocity of liquid alloy in the meltpool was within the range of 0.4–0.6 m/s, which indicates the convective heat transfer as the primary mechanism of heat transfer within the liquid pool during laser assisted additive manufacturing process. Based on a coupled thermal, fluid flow, and solidification model for the processing of single-crystal alloy CMSX-4 through scanning laser epitaxy. Acharya et al. found the flow field comprises two rotational vortices showing velocities of order 0.1 mm/s, and the Marangoni effect drives this velocity from 10 to 15 times higher depending on the operating parameters [25]. Wang et al. analyzed the fluid flow field of back-reflection induced synergistic laser welding of TC4 titanium alloy, found the maximum flow velocity is approximately 5.26 mm/s under their process conditions [26]. Khairallah et al. demonstrated the significant effect of the recoil pressure and Marangoni convection on the formation of pore defects in laser powder bed fusion of 316L stainless steel, and the maximum flow velocity was found to be approximately 9 m/s according to their numerical study [27]. In addition to different magnitudes of the melt velocity, it is proved that different flow patterns are also essential to the solidification morphology for laser-assisted manufacturing [28].

As reviewed above, although there have been many studies on the fluid characteristics of the meltpool, fewer works have related the melt flow characteristics to the evolution of the material’s microstructure. Therefore, for a sound understanding of the microstructure evolution and the demand for controlling it, it is necessary to carry out researches on the fluid characteristics of the instantaneous meltpool in relation to the microstructure evolution and to figure out the influence of manufacturing variables for such processes.

In this paper, we focus on the evolution of meltpool characteristics and the melt flow behavior in the SLM process of Ti6Al4V alloy. Based on the thermal-fluid dynamics theory, the influence of laser scanning speed on the meltpool and the internal flow field was discussed. The result was used to elucidate the formation of different material microstructures corresponding to the changed scanning speed.

2. Computational domain and basic assumptions

The calculation work was implemented using ANSYS Fluent v19.0. As the fluid calculation was very time-consuming, cubic samples with a dimension of only $5 \times 6 \times 2$ mm were employed in the present study with laser beams scanning on the top surface from the central location of one side to another side. To reduce the calculation scale, only a half symmetry volumetric model ($5 \times 3 \times 2$ mm) was created, shown in Figure 1. The model contains 240000 hexahedral cells and 252601 nodes with a uniform mesh size of 0.05 $\times$ 0.05 $\times$ 0.05 mm. The enthalpy-porosity technique was used for modeling the solidification/melting during the SLM process. In this technique, a mushy zone is modeled as a “pseudo” porous medium in which the porosity (also called the liquid fraction) in a cell decreases from 1 to 0 as the material solidifies [29]. Therefore, an entirely melt cell has a porosity of 1, and a fully solidified cell has a porosity of 0.

To simply this work, the additional assumptions made in the model include [24, 25, 30, 31]:

1. The free surface of the melt pool is flat.
2. The fluid flow in the melt pool is assumed to be Newtonian, laminar and incompressible.
3. The material has constant densities and the solid and liquid states.
4. The loss of alloying elements and the resulting compositional change owing to possible vaporization are ignored in the calculations.
5. The initial temperature is 300K, and all thermo-physical properties are constants except for the specific heat and thermal conductivity, as listed in Table 1.
6. Only gravity, buoyancy force and the surface tension of liquid metal depending on the temperature gradient are considered for driving the melt flow. The recoil pressure due to possible liquid metal evaporation was neglected.

3. Mathematical model and basic equations

3.1. Model of heat source

Allowing for the penetration effect of a laser beam in the metal powder, the laser heat input was treated as the hemispherical power density distribution model [36], in a 3D Cartesian coordinate system which can be written as
\[ q(x, y, z) = \frac{6\sqrt{3}P}{\pi R^2 \sqrt{\eta}} \exp\left(-\frac{x^2 + y^2 + z^2}{R^2}\right) \]  

(1)

where \( P \) is the laser power, \( R \) is the radius of laser spot, and \( \eta \) is the absorptivity of the material. In the present work, a constant laser power of 500 W and a constant radius of laser spot of 1 mm were considered. Although the laser power absorptivity of Ti6Al4V may be varied dependent on the elevated temperature, a constant value of \( \eta = 0.4 \) was taken for simplification as we focus mainly on the flow behavior influenced by the laser scanning speed [35].

### 3.2. Governing equations and source terms

The numerical analysis is carried out based on the classical theory of CFD. Therefore, the numerical model follows three laws of mass conservation, energy conservation and momentum conservation. The equation of mass conservation indicates the continuity of the fluid, written as

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = S_m \]  

(2)

where \( \rho \), \( \mathbf{V} \) and \( t \) denote the density of the fluid, the velocity of the fluid and time, respectively. And \( S_m \) is the source term concerning the mass added to the continuous phase from the dispersed second phase and any user-defined sources. Since the powder was prespread on the substrate, here the \( S_m \) takes a value of 0.

The equation for conservation of energy takes the following form

\[ \frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \mathbf{V} H) = \nabla \cdot (\lambda \nabla T) + S_e \]  

(3)

where \( \lambda \), \( T \), \( H \) and \( S_e \) are the thermal conductivity, temperature, enthalpy of the material and volumetric heat sources, respectively. Here the laser heat input model of Eq. (1) was included in Eq. (3) as a volumetric heat source in \( S_e \). Besides, \( H \) is computed as the sum of the sensible enthalpy and latent heat

\[ H = h_{ref} + \int_{T_{ref}}^{T} C_p dT + \Delta H \]  

(4)

where \( h_{ref} \) is the reference enthalpy corresponding to the reference temperature \( T_{ref} \), \( C_p \) and \( \Delta H \) are the specific heat and the latent heat, respectively.

### Table 1. Thermo-physical properties of Ti6Al4V.

| Material properties | Symbols | Values | Units |
|---------------------|---------|--------|-------|
| Density [31, 32]    | \( \rho \)  | 4000 kg/m\(^3\) |
| Viscosity [33]      | \( \mu \)   | 0.00236 kg/(m⋅s) |
| Specific heat [31]  | \( C_p \)  | \( 492.4 + 0.025T - 4.18 \times 10^{-6}T^2 \) J/(kg⋅K) |
| Thermal conductivity [31] | \( \lambda \) | \( 1.57 + 0.016T - 1 \times 10^{-4}T^2 \) W/(m⋅K) |
| Coefficient of thermal expansion [33] | \( \beta_T \) | \( 1.1 \times 10^{-5} \) K\(^{-1}\) |
| Latent heat of fusion [33, 34] | \( L \) | \( 2.86 \times 10^5 \) J/kg |
| Solidus temperature [31, 32] | \( T_s \) | 1878 K |
| Liquidus temperature [31, 32] | \( T_l \) | 1928 K |
| Coefficient of heat transfer [34] | \( h_c \) | 20 W/(m\(^2\)⋅K) |
| External emissivity [33, 35] | \( \delta \) | 0.65 |
| Temperature coefficient of surface tension [33] | \( \partial \gamma / \partial T \) | \( -2.8 \times 10^{-4} \) N/(m⋅K) |

Figure 1. A schematic diagram of the meshed 3D model and illustration for the laser scanning process.
The principle of momentum conservation corresponds to Newton’s second law, showing the change in the fluid momentum with respect to time in a representative volume element (RVE) equals to the sum of the forces acting on the RVE from the outside, which is written as

$$\frac{\partial}{\partial t}(\rho \vec{V}) + \nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \cdot (\vec{F}) + \rho \vec{g} + \vec{F}_s$$

(5)

where \( p \) is the static pressure, \( \vec{F} \) is the stress tensor (described below), and \( \vec{g} \) and \( \vec{F}_s \) are the gravitational acceleration and source terms for external body forces, respectively. In addition, \( \vec{F}_s \) also contains other model-dependent source terms such as porous-media and user-defined sources. In the enthalpy-porosity technique, the momentum sink due to the reduced porosity in the mushy zone takes the form

$$\vec{F}_{s1} = \frac{(1-\beta_f)^2}{\beta_f + \epsilon} A_{\text{mush}} \left( \vec{V} - \vec{V}_p \right)$$

(6)

in which \( \beta_f \) is the volume fraction of liquid, \( \epsilon \) is a small number to prevent division by zero, \( A_{\text{mush}} \) is the mushy zone constant, and \( \vec{V}_p \) is the solid velocity due to the pulling of solidified material out of the domain. The pull velocity is not considered in this study (i.e. \( \vec{V}_p = 0 \)). When the volume fraction of liquid is introduced, \( \Delta H \) in Eq. (4) is rewritten as \( \Delta H = H - \mu L \). The value of \( L \) can be found in Table 1.

Besides, the buoyancy \( F_B \) is also accounted for in \( \vec{F}_s \), which follows the Boussinesq approximation

$$\vec{F}_B = \rho \vec{g} \beta_f (T - T_\text{ref})$$

(7)

where \( \beta_f \) is the coefficient of thermal expansion and \( T_\text{ref} \) is the reference temperature. In Eq. (5), the stress tensor is detailed as

$$\vec{\Sigma} = \mu \left[ (\nabla \vec{V} + (\nabla \vec{V})^T) - \frac{2}{3} \vec{I} \cdot \nabla \vec{V} \right]$$

(8)

in which \( \mu \) is the viscosity of the melt and \( I \) is the unit tensor.

3.3. Boundary conditions

Convective and radiative boundary conditions are applied to all surfaces of the solution domain except for the symmetry plane as

$$q_{\text{conv}} = h_s (T - T_0)$$

(9)

and

$$q_{\text{rad}} = \delta \sigma (T^4 - T_\text{ref}^4)$$

(10)

where \( h_s \), \( T_0 \), \( \delta \) and \( \sigma \) are the coefficient of heat transfer, ambient temperature, emissivity and the Stefan-Boltzmann constant, respectively.

In addition to the convective and radiative boundary conditions, on the top surface of the model (c.f. Figure 1), the surface heat stress induced by the Marangoni effect is also applied as a boundary condition. The Marangoni shear stress components in \( x \)- and \( y \)-direction are given as

$$r_{xx} = -\mu \frac{\partial \vec{v}_x}{\partial x} = \frac{\partial h_s}{\partial T} \frac{\partial T}{\partial x}$$

$$r_{yy} = -\mu \frac{\partial \vec{v}_y}{\partial y} = \frac{\partial h_s}{\partial T} \frac{\partial T}{\partial y}$$

(11)

where \( \gamma \) is the surface tension at the surface temperature \( T_s \), \( \frac{\partial h_s}{\partial T} \) is the temperature coefficient of surface tension, \( \vec{v}_x \), \( \vec{v}_y \), are the \( x \)- and \( y \)-component of the flow velocity vector \( \vec{v} \). Besides, on the symmetry plane, the boundary condition is given by

$$\frac{\partial T}{\partial x} \frac{\partial \vec{V}}{\partial y} = \frac{\partial \vec{V}}{\partial y} = 0$$

(12)

4. Results and discussion

4.1. Thermal characteristics

Figure 2 describes the peak temperature evolution on the specimen during the laser scanning process. When the laser hit the top surface of the sample, the temperature increased sharply to the material’s melting point, 1878 K, within approximately 28 ms, and the first mushy zone emerged. After another 9 ms, the liquidus temperature was reached and a fully melt zone was generated. The maximum rate of temperature rise could be more than 1.4 \( \times 10^5 \) K/s. With the emergence of the mushy zone, the temperature-increasing rate began to slow down, and the peak temperature became relatively steady as the scanning time passed. Besides, a deep look into the temperature profile revealed a slow and waved ascending above the liquidus temperature. It was observed that the peak temperature and meltpool dimensions increase layer by layer for a specified combination of laser power and scanning speed [24]. During the temperature ascending process, the transient and slight drop in peak temperature, which may be due to the unsteady transition of mushy zones, was also recognized by Arrizubieta et al. both experimentally and numerically [37].

Figure 2 also shows the 3D temperature field calculated based on the thermal-fluid model for \( v_{\text{laser}} = 6 \) mm/s at 0.25 s, when the laser spot reached the central location of the scanning path. It can be seen that the maximum temperature in the specimen is above 2200 K, which appeared in the center of the laser spot and gradually decreased around it, showing nearly a contour of a hemisphere. The highest temperature is well above the liquidus temperature of Ti6Al4V (1928 K), which means melting of the material and the formation of a meltpool in the specimen. At the end of the symmetry line on the upper surface, the temperature was still on the rise at the moment with a value of 366 K; whilst behind the laser beam on the scanning path, the material was on the cooling progress after a peak temperature arrived, with the temperature of approximately 1049 K at the left end location of the symmetry line. Meanwhile, on the bottom of the specimen, the material was heated with the highest temperature of about 950 K at this moment.

The thermal history at the middle point of the laser scanning path, allowing for the influence of the scanning velocity, was shown in Figure 3. The moving heat source makes the material experienced a rapid heating and cooling process within a very short time and took a relatively long time to cool down after the laser finished scanning. When the scanning speed was 4 mm/s, the central point of the upper surface began to melt at about 0.21 s and completely solidified at about 0.635 s, keeping a liquid state for about 0.425 s. When the scanning speed was increased from 4 mm/s to 20 mm/s, this point could rapidly melt within 0.065 s and the liquid was kept only for 0.05 s, decreased by nearly 88%. Due to the effect of the latent heat, the temperature profiles showed an abrupt change in the heating and cooling rate at the melting point \( T_f \). Regarding the influence of the scanning velocity, it can be seen that a higher scanning speed would result in a lower peak temperature but a higher heating and cooling rate on the specimen. The peak temperature was 2346 K when the scanning velocity was 4 mm/s, and it dropped more than 10% to a value of 2056 K when the scanning velocity was increased to 20 mm/s. It implies that further expanding the scanning velocity may lead to insufficient fusion of the material and cause pore defects [22]. Besides, Figure 3 shows that increasing \( v_{\text{laser}} \) would result in shot time duration for metallurgical phase transition, which indicates that refined grains may be easily obtained for such cases since there was not enough time for the grain to grow [38]. However, it was also reported that the instantaneous sharp temperature change consequent to a fast scanning velocity is more likely to cause stress and deformation within the material [39].
4.2. Meltpool formation and evolution

Figure 4 illustrates the phase transition history of the central location on the top surface with the moving laser spot. It can be seen that the material generally began to melt before the laser spot reached the central location of the top surface. For \( v_{\text{laser}} = 4 \text{ mm/s} \), the laser beam would reach the midpoint after another displacement of 0.66 mm. With increasing the scanning velocity, the laser spot center would be a lot closer to the central location of the top surface when the material began to melt in this region, as illustrated in Figure 4. For instance, when the scanning velocity was increased to 20 mm/s, the gap between the center of the laser spot and that of the top surface would decrease to only 0.2 mm. Further expanding the scanning velocity would lead to the laser spot center coincides with the center of the top surface of the specimen, i.e., location of the laser beam \( x = 2.5 \text{ mm} \) in Figure 4 when the material began to melt. For such cases, the scanning velocity corresponds to a limit value above which the material cannot be melt anymore.

As the heat input diminished exponentially around the center of the laser beam, the periphery region of the laser spot may drop down rapidly to a temperature lower than the material’s solidus temperature \( T_s \) under the radiation and convection heat transfer. Therefore, the solidification process is completed under cover of the laser beam in general, as shown in Figure 4. However, if the laser beam moves slowly enough, e.g., \( v_{\text{laser}} = 4 \text{ mm/s} \), the material may still keep a liquid state for a very short time, although the laser beam had utterly passed over this point.

For different process parameters, the meltpool may show different morphological characteristics as time varied during the laser scanning process. Figure 5 exhibits the meltpool evolution under scanning velocities of 4 mm/s and 6 mm/s. It can be seen that with the movement of the laser spot under a given rate, the material at the scanning surface was partially melted firstly and formed a relatively stabilized meltpool shape.
on the specimen soon after that. Both for \( v_{\text{laser}} = 4 \text{mm/s} \) and \( v_{\text{laser}} = 6 \text{mm/s} \), a relatively stabilized hemispherical meltpool could take shape within 0.1 s, as shown in Figures 5(b) and (e). At 0.03 s for \( v_{\text{laser}} = 4 \text{mm/s} \), shown in Figure 5(a), the material was only partially melted with a maximum value of the liquid fraction of approximately 0.601. And for \( v_{\text{laser}} = 6 \text{mm/s} \), as shown in Figure 5(d), this value was reduced to about 0.585. It may be speculated that with increasing the scanning velocity, the dimension of the mushy zone would diminish until there would be no more mushy zone on the specimen within 0.03 s radiation of the moving laser beam.

Besides, Figures 5(c) and (f) show that a waved solid/liquid interface was observed at the bottom of the rear part of the molten as the time elapsed, especially for a larger scanning velocity, e.g. \( v_{\text{laser}} = 6 \text{mm/s} \), as circled in Figure 5(f). The waved solid/liquid interface may be ascribed to the dramatic change in temperature caused by a fast scanning velocity, as discussed previously in Figure 3. Since a faster scanning speed would result in a higher cooling rate, the solidification process would be more unstable, and the mushy zone became wider between the solid phase and the liquid phase.

The quantified geometric characteristics of the meltpool when the laser beam scanned to the central location of the top surface with 4 mm/s was illustrated in Figure 6. The quantitative result shows that the length (along the x-axis) of the meltpool on the top surface was about 1.51 mm, half-width on the top surface was 0.69 mm, and the maximum depth was 0.61 mm. Therefore, the exact shape of the meltpool was not actually a hemisphere but more like a semiellipsoid, and the dimension was much less than that of the heat source, of which the diameter was 2 mm. This conclusion agrees with that from Figure 4, which suggests that the material is generally melted and solidified within the region of the laser spot, i.e., under the radiation of the laser beam. In addition, the waved solid/liquid interface was also clearly observed, in Figure 6, on the symmetry plane during the cooling process.

Figure 7 depicted the influence of scanning velocities on the meltpool dimension when the laser reached the central location of the top surface. In general, the meltpool size is reduced with increased laser scanning velocity nearly in a linear relationship. When the scanning velocity was increased from 4 mm/s by five times to 20 mm/s, the pool length and width on the top surface were decreased by about 47% and 43%, respectively, to 0.71 mm and 0.60 mm. And the decrease in the maximum pool depth was even more notable with a value of 0.23 mm when \( v_{\text{laser}} = 20 \text{mm/s} \), which is only nearly 38% of that when \( v_{\text{laser}} = 4 \text{mm/s} \). The notable change in the maximum depth of the meltpool suggests that the powder thickness must be well designed to guarantee a perfect metallurgical bonding with the pre-formed substrate if a higher scanning velocity is adopted for manufacturing efficiency improvement. Although a very fast laser scanning speed may lead to insufficient fusion of the material, the super-high temperature change rate and the extremely short time duration for phase transition contribute to the grain refinement [40]. Therefore, a comprehensive study on the combination of the SLM parameters, including the laser power, is necessary for optimization before the SLM process was used industrialized for a specific material.

### 4.3. Fluid flow characteristics in the meltpool

Figure 8 shows typical fluid flow characteristics in the meltpool driven by gravity, buoyancy, and the Marangoni force. It can be seen that the flow field consists of two vortices with the center of the vortices at lower velocity, as studied by many researchers [18, 19, 24, 25]. The flow pattern shown in Figure 8 is frequently called the outward convection, which is generally ascribed to a negative value of the temperature coefficient of surface tension. It shows that on the upper surface, the melted metal flows from the center to the periphery of the meltpool and flows from the upper surface to the bottom at the edge of the meltpool. The velocity field exhibits an overall outward direction, especially at the center of the laser spot on the top surface. Besides, Figure 8 indicates that the melt flows fast in a loop band on the upper surface, especially at the two sides of the symmetry plane in the front part of the meltpool. The maximum velocity of the fluid at 0.1 s was more than 0.4 m/s, shown in Figure 8(a), and was over 0.5 m/s at 0.375 s, the moment the laser beam finished scanning half of the path, as shown in Figure 8(b). Similar magnitudes were also reported by Cui et al., who studied laser cladding of TiB/TC4 metal matrix composites [23] and by Manvatkar et al., who studied laser additive manufacturing of 316 stainless steel [24]. However, the present study shows conspicuous discrepancies compared to Wang’s calculation for laser welding of Ti6Al4V [26]. Even for the same material of 316 stainless steel, Khairallah’s work [27] showed one order higher of the melt velocity than that by Manvatkar’s study [24]. Possible reasons accounting for the above discrepancies may include the varied thermo-physical properties of the material, laser process parameters, and the numerical model itself, etc. As reviewed in the beginning part of this
Figure 4. Phase transition history of the central location on the top surface with the moving laser spot.
According to Eq. (2), the increased melt velocity may be primarily attributed to the increased temperature gradient and thermal conductivity. As described in Figure 2, the peak temperature on the specimen is gradually increased after the emergence of a full shape meltpool. Besides, the temperature gradient was also increased track by track during the laser additive manufacturing process [17]. It may suggest that the maximum velocity will rise progressively as well with the increasing time. However, compared to a longer SLM time, the liquid flow velocities in the transient meltpool may be more sensitive to the changed scanning velocity of the laser beam.

Figure 9 showed the maximum velocity of the liquid metal in the meltpool consequent to different laser scanning speeds when the laser beam traveled to the central point of the top surface. It can be seen that,
compared to the change in meltpool dimensions, the fluid velocity in the meltpool showed more close to a linear decrease with increased laser scanning speed. When the laser scanning speed was 4 mm/s, the maximum melt flow velocity was approximately 0.549 m/s according to the numerical calculation. When the laser traveling speed was 20 mm/s, the maximum melt velocity was reduced to 0.254 m/s. The linear fit in Figure 9 indicates that an increment of 2 mm/s in the scanning speed would lead to a decrease of about 0.036 m/s in the maximum flow speed of the melt.

It has been demonstrated that higher laser scanning speeds can not only result in smaller meltpool dimensions but also lead to finer grain size and higher columnar grain contents [38]. Compared to the laser power, the scanning velocity may have a more conspicuous influence on the material’s microstructure. The width of the columnar grain would expand with the decrease in the laser scanning speed, as shown in Figure 10(a) for \( \nu_{\text{laser}} = 10 \text{mm/s} \), (b) for \( \nu_{\text{laser}} = 8 \text{mm/s} \), (c) for \( \nu_{\text{laser}} = 6 \text{mm/s} \), and (d) for \( \nu_{\text{laser}} = 4 \text{mm/s} \) [41]. When the laser beam moved with a velocity of 4 mm/s, e.g. Figure 10(d), the columnar crystal would be hard to find, and instead, the microstructure showed the equiaxial crystal predominantly. Except for the lower cooling rate caused by a lower scanning speed, the higher flow velocity of liquid metal in the meltpool resulting from a lower laser scanning speed may be another possible reason for the observed microstructure influenced by the scanning speed. As depicted in Figure 9, the lower the scanning speed, the higher the liquid metal flow rate. A higher metal flow rate is more likely to break the columnar grains growing perpendicular to the solid/liquid interface. This is further confirmed by the undulation of the solid/liquid interface in the rear part of the meltpool shown in Figures 5 and 6.

In summary, a lower scanning speed results in a higher speed of melt flow, which is feasible for the formation of equiaxial grains. Although increasing the scanning rate in a laser assisted manufacturing process can improve the manufacturing efficiency to some extent, it also reduces the peak temperature of the localized metallurgical phase transition process and the dimension of the transient meltpool. Besides, the heating and cooling rate is enhanced by a higher scanning rate. The short duration of the meltpool and the sharp decline in temperature can prevent the formation of coarse grains and thus improve the material’s mechanical properties consequent to the laser additive manufacturing process. Nevertheless, adverse effects of higher scanning rates are that the thermal stress caused by rapid heating and cooling may be higher, and the insufficient fusion and pores may prevail due to the reduced peak temperature and meltpool dimension. Therefore, when design the process parameters of a laser additive manufacturing process, many factors such as the manufacturing efficiency, microstructure morphology, grain
morphology and size, thermal stress, and deformation should be considered comprehensively for a specific material so as to obtain the optimized combination of process parameters for industrial application.

5. Conclusions

To account for the microstructure evolution corresponding to the changed scanning speed, the thermal-fluid dynamic model of the selective laser melting (SLM) process of Ti6Al4V alloy was established by numerical method to study the thermal characteristics and the fluid dynamics of the melt pool. The following conclusions can be drawn:

- During a laser additive manufacturing process, the rate of temperature rise could be over $10^5$ K/s, and the material is generally melted within tens of milliseconds. After the formation of a full shape melt pool, the peak temperature would still gradually ascend as long as the scanning process continues. Increasing the laser scanning speed would result in a lower peak temperature but a higher heating and cooling rate on the specimen.
- Both the melt pool size and its duration were reduced with the increased laser scanning velocity. A waved solid/liquid interface was observed at the bottom of the rear part of the melt pool as the time elapsed, especially for a larger scanning velocity, which shows a more unstable solidification process and may be attributed to the fierce thermal effect caused by a more significant scanning velocity.
- The fluid flow characteristics in the melt pool driven by gravity, buoyancy, and the Marangoni force showed outward convection which consists of two vortices. The flow velocity had a magnitude of hundreds of millimeters per second and showed nearly a linear decline with the increased laser scanning speed.
- Higher scanning speeds can not only result in smaller melt pool dimensions but also lead to finer grain size and higher columnar grain contents. The predominant equiaxial grains observed under lower laser scanning rates may be ascribed to the higher flow velocity of liquid metal in the melt pool resulted from a lower laser scanning speed.

Figure 9. Maximum velocity of the melt consequent to different laser scanning speeds.

Figure 10. Influence of scanning speed on the microstructure of laser deposited Ti6Al4V ($P = 500$W): (a) $v_{\text{laser}} = 10$mm/s; (b) $v_{\text{laser}} = 8$mm/s; (c) $v_{\text{laser}} = 6$mm/s; (d) $v_{\text{laser}} = 4$mm/s [41].
speed, except for the lower cooling rate caused by a lower scanning speed.

- Although increasing the scanning rate in the SLM process can improve the manufacturing efficiency to some extent and feasible for refined grains, higher scanning rates are more likely to cause a high level of thermal stress and insufficient fusion and pores. Therefore, the scanning velocity must be tailored carefully, allowing for its possible influence on the microstructure morphology, grain morphology and size, thermal stress, and deformation, etc.

Due to the high computational cost, the present work was limited to a single-track laser scanning on a small geometric model. In the future, multiple scanning routes will be considered while taking into account the size effect if possible. Besides, we will also work on the interaction between powder particles using the discrete element method and its influence on the flow characteristics of the meltpool and the free surface morphology.

Declarations

Author contribution statement

Chao Zeng: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; wrote the paper.

Yun Jia: analyzed and interpreted the data; contributed reagents, materials, analysis tools or data.

Jitian Xu: performed the experiments; contributed reagents, materials, analysis tools or data.

Xiayao Liu: analyzed and interpreted the data.

Qingqing Dong: performed the experiments.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] D. Gu, X. Shi, R. Poprawe, et al., Material-structure-performance integrated laser-metal additive manufacturing, Science 372 (6545) (2021), eabc1487.
[2] S. Liu, Y.C. Shin, Additive manufacturing of Ti6Al4V alloy: a review, Mater. Des. 164 (2019), 107552.
[3] H. Wang, Materials’ fundamental issues of laser additive manufacturing for high performance large metallic components, Acta Aeronautica Astronautica Sinica 35 (10) (2014) 2690–2698.
[4] H. Ali, H. Glaudemans, K. Muntaz, Effect of scanning strategies on residual stress and mechanical properties of Selective Laser Melted Ti6Al4V, Mater. Sci. Eng. A 712 (2018) 175–187.
[5] A.K. Singla, M. Banejee, A. Sharma, et al., Selective laser melting of Ti6Al4V alloy: process parameters, defects and post-treatments, J. Manuf. Process. 64 (2021) 161–187.
[6] X. Yang, R.A. Barrett, M. Tong, et al., Prediction of microstructure evolution for additive manufacturing of Ti–6Al–4V, Procedia Manuf. 47 (2020) 1178–1183.
[7] L. Todd, Printing steels, Nat. Mater. 17 (1) (2018) 13–14.
[8] R. Chen, H.J. Kong, J.H. Luan, et al., Effect of external applied magnetic field on microstructures and mechanical properties of laser welding joint of middle-Mn nanostructured steel, Mater. Sci. Eng. A 792 (2020), 139787.
[9] Y. Hu, L. Wang, J. Yao, et al., Effects of electromagnetic compound field on the escape behavior of pores in molten pool during laser cladding, Surf. Coating. Technol. 383 (2020), 125196.
[10] G.A. Tilia, W. Chen, R. Ma, et al., Effect of ultrasonic excitation on the process of L-PBFAM, J. Mater. Process. Technol. 277 (2020), 116436.
[11] G. Hu, Y. Yang, R. Sun, et al., Microstructure and properties of laser cladding NiCrBSi coating assisted by electromagnetic-ultrasonic additive manufacturing field, Surf. Coating. Technol. 404 (2020), 126469.
[12] C. Li, S. Sun, C. Liu, et al., Microstructure and mechanical properties of TiC/AlCr10NiMo alloy fabricated by laser additive manufacturing under high-frequency micro-vibration, J. Alloys Compd. 794 (2019) 236–246.
[13] L. Zhai, Q. Wang, J. Zhang, et al., Effect of alternating current electric field on microstructure and properties of laser cladding NiCr-3Si-B coating, Ceram. Int. 45 (14) (2019) 16675–16689.
[14] T. Zhang, P. Li, J. Zhou, et al., Microstructure evolution of laser cladding Inconel 718 assisted hybrid ultrasonic-electromagnetic field, Mater. Lett. 289 (2021), 129401.
[15] Y. Yang, E. Zhao, L. Qin, et al., Effect of electromagnetic stirring on melt flow velocity of laser melt pool and solidification structure, Houchuang VII/Gongcheng/Infrared and Laser Engineering 46 (9) (2017) 48–55.
[16] H. Gu, C. Wei, L. Li, et al., Multi-physics modeling of molten pool development and track formation in multi-track, multi-layer and multi-material selective laser melting, Int. J. Heat Mass Trans. 151 (2020), 119458.
[17] Y.S. Lee, W. Zhang, Modeling of heat transfer, fluid flow and solidification microstructure of nickel-base superalloy fabricated by laser powder bed fusion, Addit. Manuf. 12 (2016) 178–188.
[18] Z. Li, G. Yu, X. He, et al., Analysis of surface tension driven flow and solidification behavior in laser linear welding of stainless steel, Opt. Laser. Technol. 123 (2020), 105914.
[19] D. Zheng, P. Zhang, Z. Liu, et al., Thermofluid field of molten pool and its effects during selective laser melting (SLM) of Inconel 718 alloy, Addit. Manuf. 21 (2018) 567–578.
[20] C. Panwisawis, C.L. Qiu, Y. Sovani, et al., On the role of thermal fluid dynamics into the evolution of porosity during selective laser melting, Scripta Mater. 105 (2015) 14–17.
[21] C. Qiu, C. Panwisawis, M. Ward, et al., On the role of melt flow into the surface structure and porosity development during selective laser melting, Acta Mater. 96 (2015) 72–79.
[22] L. Cao, Mesoscopic-scale simulation of pore evolution during laser powder bed fusion process, Comput. Mater. Sci. 179 (2020), 109686.
[23] C. Cai, C. Fang, W. Zhang, Effects of Marangoni flow on the thermal behavior and melt flow behavior in laser cladding, Yingyou Jiguang/ APPLIED LASER 38 (3) (2018) 409–416.
[24] V. Manvatkar, A. De, T. DebRoy, Spatial variation of melt pool geometry, peak temperature and solidification parameters during laser assisted additive manufacturing process, Mater. Sci. Technol. 31 (8) (2015) 924–930.
[25] R. Acharya, R. Bansal, J.J. Gambone, et al., A coupled thermal, fluid flow and solidification model for the processing of single-crystal alloy CMSX-4 through scanning laser epitaxy for turbine engine hot section component repair (Part I), Metall. Mater. Trans. B 45 (6) (2014) 2247–2261.
[26] H. Wang, R. Ding, A. Huang, et al., Analysis on keyhole phase change and flow field of back reflection induced synergistic laser weld, Hanjie Xuebao/Trans. China Weld. Institution 39 (5) (2018) 125–128 +134.
[27] S.A. Khairallah, A.T. Anderson, A. Rubenchik, et al., Laser powder-bed fusion additive manufacturing: physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones, Acta Mater. 108 (2016) 36–45.
[28] G. Ma, L. Li, Y. Chen, Comparative study of molten pool behavior and weld formation characteristics in single/dual beam laser welding, Zhongguo Jiguang/ Chin. J. Laser. 44 (2) (2017) 225–233.
[29] V.R. Voller, C. Prakash, A fixed grid numerical modelling methodology for convection-diffusion mushy region phase-change problems, Int. J. Heat Mass Trans. 30 (8) (1987) 1709–1719.
[30] Z. Gan, G. Yu, X. He, et al., Surface-active element transport and its effect on liquid metal flow in laser-assisted additive manufacturing, Int. Commun. Heat Mass Trans. 86 (2017) 206–214.
[31] T. Mukherjee, W. Zhang, T. DebRoy, An improved prediction of residual stresses and distortion in additive manufacturing, Comput. Mater. Sci. 126 (Supplement C) (2017) 360–372.
[32] R. Bao, J.W. Elmer, T.A. Palmer, et al., Heat transfer and fluid flow during keyhole mode laser welding of tantalum, Ti–6Al–4V, 304L stainless steel and vanadium, J. Phys. D Appl. Phys. 40 (18) (2007) 5753–5766.
[33] A.K. Mishra, A. Kumar, Numerical and experimental analysis of the effect of volumetric energy absorption in powder layer on thermal-fluidic transport in selective laser melting of Ti6Al4V, Opt Laser. Technol. 111 (2019) 227–239.
[34] S. Hocine, H. Van Swygenhoven, S. Van Petegem, Verification of selective laser melting heat source models with openuo X-ray diffraction data, Addit. Manuf. 37 (2021), 101747.
[35] P. Prompoppatum, R. Oiler, S.-C. Yao, Numerical and experimental investigations of micro and macro characteristics of direct metal laser sintered Ti–6Al–4V products, J. Mater. Process. Technol. 240 (2017) 262–273.
[36] J. Goldak, A. Chakravarti, M. Bibby, A new finite element model for welding heat sources, Metall. Trans. A B 15 (2) (1984) 299–305.
[37] U. Verzini, W. Lien, K. Flocke, et al., Evaluation of the relevance of melt pool dynamics in Laser Material Deposition process modeling, Int. J. Heat Mass Trans. 115 (2017) 80–91.
[38] Y. Zhang, J. Zhang, Modeling of solidification microstructure evolution in laser powder bed fusion fabricated 316L stainless steel using combined computational fluid dynamics and cellular automata, Addit. Manuf. 28 (2019) 750–765.

[39] D.D. Gu, D.H. Dai, M.J. Xia, et al., Cross-Scale physical mechanisms for structure and performance control of metal components processed by selective laser melting additive manufacturing, J. Nanjing Univ. Aeronaut. Astronaut. 49 (5) (2017) 645–652.

[40] B. Zhou, J. Zhou, H. Li, et al., A study of the microstructures and mechanical properties of Ti6Al4V fabricated by SLM under vacuum, Mater. Sci. Eng. A 724 (2018) 1–10.

[41] L. Li, J. Wang, C. Wu, et al., Temperature field of molten pool and microstructure property in laser melting depositions of Ti6Al4V, Zhongguo Jiguang/Chin. J. Laser. 44 (3) (2017) 119–126.