Improving additive manufacturing processability of hard-to-process overhanging structure by selective laser melting

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ABSTRACT

In this paper, a selective laser melting (SLM) physical model describing the melt pool dynamics and the response of downward-facing surface morphology evolution of overhanging structure under different laser processing conditions was proposed, in which an enormous difference in thermal conductivity and laser absorption capacity between the as-fabricated part and powder material was taken into consideration. The underlying thermal physical mechanism of the droop formation phenomenon during SLM preparing overhanging surface was revealed by numerical simulation analysis and experimental studies. It was found that both high and low laser volume energy density ($\omega$) resulted in an inferior downward-facing surface quality. As an optimal processing parameter ($60\text{–}80\text{ J/mm}^3$) was settled, the overhanging structure obtained a relatively smooth downward-facing surface due to the sound melt pool dimension and steady melt flow behavior. The experimental studies were compared with the simulated results, showing a good agreement with the predictions obtained in the simulations. It was interesting to find that the variation rules of surface quality and densification level of overhanging structure with different $\omega$ were exactly converse. As the $\omega$ decreased from 80 J/mm$^3$ to 60 J/mm$^3$, the surface roughness could be reduced from 59 $\mu$m to 33 $\mu$m while, contrarily, the porosity was elevated from 3.2% to 8.4%. In order to fabricate complicated metal parts with lower risk, four solutions for improving the processability of hard-to-process overhanging structure were provided.

1. Introduction

Additive manufacturing (AM) of metal parts has obtained big market share recently, owing to improvements in technologies and introduction of novel metal powders which are adequate for metal components with applications in many fields such as aerospace, automotive or medical industries (Boschetto et al., 2017). Selective laser melting (SLM) is a popular AM process that can realize the rapid prototyping of complex-shaped three-dimensional (3D) products directly from metal powder (Wang et al., 2016a,b). A laser beam is used to selectively melt and solidify material in a powder-bed according to slices of corresponding 3D model, and the process repeats in a layer-by-layer manner until the product is finished (Sistiaga et al., 2016). Recently, numbers of researches have reported that SLM, due to its flexibility in feedstock and shapes, has a high potential to fabricate topologically optimized structures (Liu et al., 2015), negative Poisson’s ratio structures (Li et al., 2016), cellular lattice structures (Leary et al., 2016) and foam materials (Matsumoto et al., 2016) with intricate interior structure, which are extremely hard to prepare using traditional processing methods (Gu, 2016). These complicated structures generally possess large numbers of overhanging surfaces. In theory, any complex parts can be manufactured by SLM; however in practical, not all geometrical features can be perfectly fabricated (Gu and Wong, 2016). The overhanging surface, which is also called downward-facing surface, is the hardest part to fabricate in SLM process and it generally makes the final product’s dimensional accuracy and shape come short of the corresponding requirements. Therefore, external support structures are required during the fabrication of overhanging structures to fix the part to the building platform and conduct excess heat away from the part, hence preventing the warping and/or collapse (Calignano, 2014). Nevertheless, when the parts are considerably intricate, and the overhanging surfaces are inside the parts, adding and removing support structures become quite difficult. On the other hand, the employment of support structures increases both manufacturing time and the
complexity of post-processing operations. As such, minimizing the amount of support structures can significantly promote the process efficiency and it would be of great significance for the improvement of SLM technique and its application scope.

Compared with other surfaces of SLM-processed parts, the overhanging surface is generally characterized to possess the highest surface roughness (Vandenbroucke and Kruth, 2007). According to Yadroitsev et al. (2009)’s research, the main fabricating defects that often exist in the overhanging surface are staircase effect, warp and dross formation.

Staircase effect is an inevitable phenomenon happening during the fabrication of overhanging structures. Before processing, the computer-aided design model of the part should be sliced into large amounts of thin layers and the overhanging length \( L_o \) between adjacent two layers can be determined as follow (Yadroitsev et al., 2007):

\[
L_o = \frac{h}{\tan \theta}
\]

where \( h \) is the layer thickness, \( \theta \) is the inclined angle, which is defined as the angle between the horizontal plane and the tangent line of a certain surface. Eq. (1) indicates that a decrease of the inclined angle \( \theta \) can result in a larger overhanging length \( L_o \) and hence give rise to a prominent staircase effect, which would adversely affect the processing quality of the overhanging structures. It is apparent that the employment of a thinner powder layer (a reduced layer thickness \( h \)) would alleviate the occurrence of staircase effect. Warping is another non-negligible fabricating defect during SLM. The temperature gradient mechanism (TGM) (Kruth et al., 2004) can be applicable in SLM in which it acts on previously fabricated layers lying beneath the processed powder layer. Due to the rapid heating of the upper surface scanned by the high energy laser beam, a significantly steep temperature gradient develops and hence causes various deformation behaviors in different heated areas. Then, the thermal stresses form during the process of the rapid solidification of melt pool and a bending angle towards the laser beam develops. From Zhao et al. (2009)’s results, it appears that thermal residual stresses concentrate on both edges of the scanning track and a low scanning velocity can lead to a high cooling rate, hence causing larger thermal residual stresses. As such, there are two effective methods for reducing deformations during the SLM process: set appropriate powder bed preheating temperature and perform laser remelting (Zhang et al., 2013).

Dross formation is regarded as the most unpredictable and hard-to-control fabricating defect of SLM, which would result in large surface roughness and bad geometry accuracy of overhanging surfaces (Wang et al., 2016a,b). Triantaphyllou et al. (2015) investigated the upward and downward-facing surface roughness for varying angles, compared results from multiple measurement instruments, and found that the Ssk parameter can be used for differentiating between upward- and downward-facing surfaces. Wang et al. (2013) designed a series of experiments to study the influence of inclined angle, scanning speed, laser power, accumulated residual stress, and scanning vector length on overhanging surface fabrication. Clijsters et al. (2014) developed an in situ quality control method of the laser-powder interaction process using a high-speed, real-time melt pool monitoring system. However, it is difficult to understand the underlying mechanism of the defect formation of overhanging surface through experimental methods. Numerical simulation of SLM process is necessary to disclose the melt pool thermal behavior and detailed fluid flow mechanism when processing overhanging structure. Kovalev and Gurin (2014) developed a three-dimensional multivortex model to simulate two-phase thermo-hydrodynamic flows in laser induced melt pool of a steel substrate. It was found that the fluid flow within the melt pool played a significant role in the mechanisms of heat and mass redistribution. Matthews et al. (2016) studied the denudation behavior of metal powders through finite element simulations. Their results showed that the observed depletion of metal powder particles in the zone immediately surrounding the solidified track was due to a competition between outward metal vapor flux directed away from the laser spot and entrainment of powder particles in a shear flow of gas driven by a metal vapor jet at the melt track. Khairallah et al. (2016) studied the physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones by establishing a three-dimensional high fidelity powder-scale model. They believed that the strong dynamical melt flow generated pore defects, material spattering (sparking), and denudation zones. Nevertheless, little simulation researches have been conducted to model the fabrication process of overhanging structure by SLM. It is worth noting that there is a lack of understanding of the underlying thermal physical mechanism of the dross formation of overhanging surface by SLM.

In this study, the numerical simulation in consideration of the physical property diversity in both sides of the laser scan track, taking account of the influence of various processing conditions on the melt pool dynamics and the attendant thermal-capillary convection during the fabrication of overhanging structure by SLM, was proposed. In order to reveal the underlying thermal mechanism of dross formation of overhanging parts under different laser processing conditions, the temperature field, temperature gradient, and the thermo-capillary convection intensity in the melt pool under various processing parameters were simulated. Additionally, the morphologies of overhanging surface predicted by numerical simulation were compared with these gained by experiments, so as to verify the accuracy of the developed simulation model and obtain the optimized SLM processing conditions.

2. Numerical approach

2.1. Physical model description

As is known to all, there are significant differences in laser absorptivity and heat conductivity between the solid material and powder material. As shown in Fig. 1, when laser irradiates the powder materials zones, severe heat accumulation will occur at the laser-powder interaction area, hence causing a relative large melt pool dimension compared to that in the solidified part, due to the lower heat conduction rate and higher laser absorptivity of powder materials compared with the solid material.

Based on above considerations, the schematic of the SLM processing overhanging structure is demonstrated in Fig. 2(a). The laser energy used in this work is estimated as a heat flux, which is defined as a Gaussian function. The three dimensions of the numerical model are 200 μm × 200 μm × 150 μm in the X-, Y-, and Z-axis directions. The inclined angle θ of the overhanging surface is 15. The interaction part scanned by the laser beam is representatively composed of the as-fabricated zone and powder material zone. The contact surface of bulk materials and powder materials is defined as an interface shared by the two zones. The initial ambient temperature of the physical model is set as 300 K. The calculation is conducted with a structured mesh composed of 150000 hexahedral cells. The mathematical model, based on the Navier-Stokes equations, is employed in this work. The governing equations, composed of the conservation of the mass, momentum and
energy, the heat flux input with the heat loss caused by the convection and radiation, the evaporation modes, the Gaussian heat source, the properties of as-used materials (bulk materials and powder materials) and the convergence principle of the calculations have been described in our previous work (Gu and Dai, 2016) in detail. It is important to mention that the predicted melt pool dynamics and dimensions are only representative due to the assumption of a continuum domain of the proposed model.

2.2. Numerical simulation

The FLUENT commercial finite volume method (FVM) package (version 6.3.26) is used in this numerical simulation to predict the melt pool thermal behavior and the response of downward-facing surface morphology evolution of overhanging structure. The temperature field obtained in the simulation process is shown in Fig. 2. According to Sih and Barlow (2004)’s research, the thermal conductivity of AlSi10Mg material is depicted in Fig. 3. The absorptivity of solid material and powder material used in this study is based on Boley et al. (2015)’s study. The optimized SLM processing parameters based on our previous study (Xiong et al., 2017) are shown: laser power (P), hatch space (s) and the thickness of the powder layer (h) at 300W, 50 μm and 50 μm, respectively. In order to change the processing conditions during SLM process, different laser scan speed (v = 1000 mm/s, 1500 mm/s, 2000 mm/s and 2500 mm/s) were set by the system control program. Therefore, four different “volume energy densities” (ω) of 120 J/mm³, 80 J/mm³, 60 J/mm³, 48 J/mm³, which were defined by:

\[ \omega = \frac{P}{vsh} \]

were employed to evaluate the laser energy input to the powder layer being processed.

3. Experimental procedure

The 99.7% purity AlSi10Mg powder with a spherical shape and a mean particle size of 30 μm was used in this experiment. The SLM apparatus mainly consisted of a YLR-500 ytterbium fiber laser with a maximum output power of 500W and a spot size of 70 μm (IPG Laser GmbH, Germany), an automatic powder spreading device, an inert argon gas protection system, and a computer system for the process control. Details of SLM processing procedures have been addressed in our previous work (Gu et al., 2012). The typical downward-facing surface morphology and microstructure study of the SLM-processed overhanging parts was performed using a PMG3 optical microscopy (OM; Olympus Corporation, Tokyo, Japan) and a S-4800 field emission SEM (FE-SEM) (Hitachi, Japan) at 5 kV.

4. Results and discussion

4.1. Temperature distribution and melt pool dimensions

Fig. 4 depicts the representative temperature distribution of the cross-section of the melt pool under various laser processing parameters. Owing to the enormous difference in the thermo-physical properties, e.g., the thermal conductivity, the absorption of the laser energy, and the resultant heat loss between solidified part and powder material, the operative temperature obtained in the powder zone is considerably larger than that obtained in the as-fabricated zone, showing an asymmetric temperature distribution against X-Z plane. Fig. 5 shows the temperature distribution along Y-axis direction and melt pool dimensions using different laser parameters. It can be found that the operative temperature during the SLM process and corresponding melt pool dimensions consistently increase with the ω enhancing. It should be noted that the width and depth of melt pool are quite close at all given parameters, which causes the melt pool to show a narrow and deeper configuration. According to previous study (Gu and Yuan, 2015), during the SLM process of Al-alloy, the temperature field is symmetrical against the X-Z plane and the melt pool geometry generally shows a shallow and wide shape. However, the above study neglects the difference of thermal conductivity and laser absorption capacity between powder zone and as-fabricated zone. It is worth noticing that the thermal conductivity of powder material is only 1/100 of the solid material (Fig. 3) and thus the heat energy is confoundedly hard to be conducted through the powder zone, hence causing a significant large temperature gradient along the +Y-axis (Fig. 5(a)). While, the as-fabricated part, possessing an efficient thermal-conductivity about 230 J/(mK), accelerates the dramatic heat loss from the irradiated region to the ambient, leading to a lower operative
temperature and smaller temperature gradient in the melt pool. Additionally, in previous study (Gu and Yuan, 2015), at the first iteration time step, the heat dissipation mode is defined as conducted by powder materials and air. Nevertheless, obviously, in $-Z$ direction, the substantial heat energy accumulated in powder zone can be effectively conducted through the as-fabricated part, which is of great help to enhance the laser penetration depth and increase the depth of melt pool. As the $\omega$ is 120 J/mm$^3$ ($v = 1000$ mm/s), the maximal operative temperature during the SLM process in the powder zone is 1480 K and, the width and depth obtained within the melt pool are 107 $\mu$m and 95 $\mu$m, respectively. The overlarge melt pool can significantly give rise to the sinking defects of the overhanging surface and result in a poor surface finish. As the $\omega$ decreases to 80 J/mm$^3$ (1500 mm/s), the maximal operative temperature, the width and depth obtained within the melt pool respectively declines to 1375 K, 70 $\mu$m and 65 $\mu$m, due to the reduced energy input and shorter laser-powder interaction time. The formation of a smaller melt pool can alleviate the occurrence of dross formation and improve the downward-facing surface fabrication quality significantly. As the $\omega$ further decreases to 60 J/mm$^3$ (2000 mm/s), the maximum operative temperature obtained in the

![Fig. 4. Temperature distribution of the cross-sections within the melt pool using different processing parameters: (a) 120 J/mm$^3$; (b) 80 J/mm$^3$; (c) 60 J/mm$^3$; (d) 48 J/mm$^3$.](image)

![Fig. 5. (a) The temperature distribution along Y direction and (b) melt pool dimensions using different laser parameters.](image)
The temperature gradient along Y direction using different laser parameters.

Fig. 6. The temperature gradient along Y direction using different laser parameters.

powder material area reduces to 1210 K and it can be deduced that the gross formation phenomenon can be effectively inhibited resulted from the limited dimensions of melt pool. However, the remelting area in the as-fabricated part is appreciably smaller, leading to a discontinuous melt pool. This can be detrimental to the metallurgical bonding ability between the neighboring tracks. When the \( T \) is settled at the lowest value of 48 J/mm\(^3\) (2500 mm/s), the remelting region disappears and the dimension of melt pool in the powder zone tremendously decreases, due to the seriously inadequate absorbed laser energy and resultant low operative temperature when using an extraordinarily rapid laser scan speed. In this situation, the metallurgical bonding ability between the neighboring tracks and interlayers will be fairly unfavorable, which can result in a poor surface quality and low densification level of overhanging structure. In conclusion, as an overlarge volume energy density \( \omega \) (120 J/mm\(^3\)) is applied, the powder material is overheated, hence leading to the formation of oversized melt pool and resulting in the serious gross defects. Using a considerably low \( \omega \) (48 J/mm\(^3\)) can effectively reduce the dimension of melt pool but give rise to the partial/non-melting of the as-fabricated part and cause unfavourable bonding between neighbouring melt tracks, which is detrimental to the successful fabrication of SLM-processed overhanging part with full density. As such, the optimized volume energy density \( \omega \) is believed to be in the range of 60–80 J/mm\(^3\) (laser power \( P \), hatch space \( s \) and layer thickness \( h \) are set at the optimized values of 300W, 50 \( \mu \)m and 50 \( \mu \)m, respectively).

4.2. Melt flow behavior

Due to the introduction of Gaussian distribution laser heat source, tremendous temperature gradients form within the laser-induced melt pool. The surface tension \( \gamma \) of the Al-alloy melt, considerably depending on the operative temperature \( T \) can be expressed as follow (Dou et al., 2008):

\[
\gamma = [868 - 0.152(T - T_m)] \times 10^{-3}(T > 873.2K)
\]

(3)

where \( T_m \) is the melting point of Al-alloy. It can be deduced that the large temperature gradient will generate a considerable surface tension gradient, which causes Marangoni convection flowing from low surface tension region to high surface tension region within the melt pool. On account of that the \( \frac{d\gamma}{dT} \) is negative, the melt is prone to flow away from the center to the edge of the melt pool, hence causing an outward flow pattern of the liquid. The previous study (Gu and Yuan, 2015) revealed that the Marangoni flow within the melt pool exhibited a symmetrical outward convection mode, due to the symmetrical Marangoni tension against the X-Z plane. However, this is unconnected to the real situations, to some degree. This is because the remarkable temperature gradient diversity of as-fabricated parts and powder materials can change the convection type and intensity of Marangoni flow, which greatly affects the thermal behavior of melt pool and modifies the melt pool configuration. Additionally, based on Dai and Gu (2015)’s investigation, the serious surface tension difference gives rise to various melt flow behavior in different region of melt pool and results in serious fluctuation of melt pool, hence causing fabrication defects such as key holes and material stacking. As such, the distinctive and sophisticated melt flow behavior during the fabrication of overhanging structure can cause an aberrant morphology of the melt pool.

According to Kruth et al. (2007)’s research, the dimensionless Marangoni number \( M_d \) can be assessed by:

\[
M_d = \frac{d\gamma}{dT} \left( \frac{T}{\mu} \right)
\]

where \( d\gamma/dT \) is the temperature gradient within the melt pool, \( \mu \) is the linear size of the pool, \( \kappa \) is the thermal diffusivity and \( \gamma \) is the dynamic viscosity. As such, the \( M_d \) is determined by the temperature gradient \( d\gamma/dx \), the dimension of melt pool and the dynamic viscosity of liquid simultaneously. The dynamic viscosity \( \mu \) of the melt can be determined as (Gu et al., 2012):

\[
\mu = \frac{16}{15} \frac{m}{k_B T^3}
\]

(4)

where \( m \) is the atomic mass, \( k_B \) represents the Boltzmann constant. The temperature gradients along Y direction using different laser parameters are calculated and given in Fig. 6 quantificationally. It can be seen that there is an enormous difference in the maximal temperature gradient between powder zone and as-fabricated zone; the temperature gradients in all regions constantly reduce with the applied \( \omega \) decreasing. As the \( \omega \) is applied at 120 J/mm\(^3\), the maximal temperature gradient in powder zone and as-fabricated zone is 1.47 × 10\(^7\) K/m and 6.45 × 10\(^6\) K/m, respectively. Meanwhile, a small scan speed \( v \) corresponds to an elevated operative \( T \), due to the longer dwelling time of the laser beam on the surface of melt pool. According to Eq. (5), a high \( T \) can significantly decrease the dynamic viscosity \( \mu \), indicating a weaker shearing force in liquids. As such, an enormous temperature gradient, a significantly reduced dynamic viscosity \( \mu \) and a large dimension of melt pool can lead to an enhanced \( M_d \) (Eq. (4)), hence re-inforcing the ability of melt flow strongly. Fig. 7 gives the velocity field within the cross-sections of the melt pool using different processing parameters. It can be seen that, when the \( \omega \) is 120 J/mm\(^3\), the maximal melt flow velocity within melt pool is calculated about 15.7 m/s (Fig. 7(a)); the location of the maximal melt flow velocity is located at 21.2 \( \mu \)m, which is highly corresponding to the location of the maximal temperature gradient as shown in Fig. 6. From Fig. 7(a), it can be seen that the Marangoni flow exhibits a radially outward flow pattern and, the upward direction of the melt in the region, \( Z \geq 27.5 \mu \)m, with the average melt velocity of 4 m/s indicates the formation of the evaporation phenomenon caused by the overheating of the melt irradiated by the laser beam. This can cause significant spatter phenomenon during selective laser melting and induce liquid fluctuation phenomenon. Generally, the orientation of Marangoni convection implies the direction of heat and mass transfer within the melt. Even though the life time of melt pool is very short (0.5–1 ms), the rapid heat and mass transfer phenomenon driven by Marangoni flow can significantly influence the final configuration of melt pool. Conspicuously, the melt flow velocity variation in different locations of melt pool would result in the heterogeneous distribution of materials. For example, at (Y, Z) = (21.2 \( \mu \)m, 50 \( \mu \)m), the melt flow velocity is very large while it is much smaller at the rear region (e.g. (Y, Z) = (15 \( \mu \)m, 50 \( \mu \)m)). It can be inferred that, after the lifetime of melt pool, the materials where (Y, Z) = (21.2 \( \mu \)m, 50 \( \mu \)m) will be lacking and the attendant keyhole collapse will be generated at this place. Meanwhile, materials stacking will form at the front region (e.g. (Y, Z) = (30 \( \mu \)m, 50 \( \mu \)m)), hence causing the fluctuation of melt pool as showing in Fig. 8(a). Owing to the situation
that all the melt materials in the center of the melt pool have a high tendency to flow towards the peripheral part, severe materials stacking at the periphery of melt pool will occur (as selective marked in Fig. 8(a)). In addition, the vector of the velocity field located at the tip of downward-facing surface, as selectively indicated in Fig. 7(a), is inclined to encounter along the overhanging-powder interface, hence accelerating the dross formation and decreasing the surface quality of the overhanging surface (Fig. 8(a)). As $\omega$ decreases to 80 J/mm$^3$, the maximum flow velocity drastically decreases to 8.7 m/s (Fig. 7(b)) and its location is shifted from the surface to the interior of melt pool. In this situation, reduced Marangoni effect mainly occurs in the interior of melt pool and accordingly its influence on the surface morphology will be mitigating (Xiao and Zhang, 2007). As $\omega$ further decreases to 60 J/mm$^3$, the maximum flow velocity is calculated about 7.1 m/s (Fig. 7(c)). In this situation, the melt flow behavior is believed to be mild and brings fewer disturbances to the melt pool. Thus, a steadier melt pool will form and the dross formation can be alleviated as a moderate $\omega$ (80 or 60 J/mm$^3$) is applied (Fig. 8(b)). As the $\omega$ decreases to the lowest value of 48 J/mm$^3$, the low energy input brings a violent instability to the moving melt pool. In order to reach the equilibrium state, the melt flow will exhibit an inward backflow pattern (Fig. 7(d)) and the melting track is prone to break up into spherical agglomerate driven by the capillary forces (Fig. 8(c)). This could bring the large irregular-shaped pores to the SLM-processed parts and lower the manufacturability of overhanging structure.

4.3. Experimental verification

The cross-section of overhanging part fabricated by SLM and corresponding original CAD data are shown in Fig. 9. The dross formation phenomenon occurring at the downward-facing surface could be clearly observed. Detailed SEM studies of the corresponding morphologies of overhanging surfaces using different laser processing parameters are characterized in Fig. 10. At a relatively high $\omega$ of 120 J/mm$^3$, large-sized agglomerate was present on the overhanging surface of the SLM-processed part, due to the excessive laser energy input. Poor metallurgical bonding between interlayers could be observed (as marked in Fig. 10(a)), demonstrating the severe fluctuation of melt pool as a high $\omega$ was applied. Meanwhile, the agglomerate showed an asymmetric morphology against the center line and, some projections could be observed to form at the periphery of the agglomerate, verifying the significant influence of melt flow behavior on the final morphology of melt pool. As the $\omega$ decreased to 80 J/mm$^3$, the agglomerate effect was significantly alleviated, due to the reduced dimension of melt pool and inhibited Marangoni effect, hence improving the fabrication quality of overhanging surface. As the $\omega$ further decreased to 60 J/mm$^3$, the surface quality of the overhanging part was observed to be favorable. Nevertheless, some metallurgical defects could be observed on the cross-section of overhanging part. As the $\omega$ decreased to the lowest value of 48 J/mm$^3$, serious materials spalling phenomenon was produced on the overhanging surface of SLM-processed parts, owing to the “balling” effect and resultant poor interlayer bonding. Some residual pores were also present on the cross-section of overhanging structure.
due to the insufficient laser energy input and resultant limited metallurgical bonding between adjacent melting tracks.

A good surface quality is critical in many applications, because a better surface quality can avoid the formation of surface initiated cracking. However, when subjected to random loading in service, the cracks and pores within SLM-processed parts always act as crack initiation sites and result in premature failure. As such, both surface quality and densification level can remarkably influence the mechanical performance of SLM-processed parts. In order to improve the processability of overhanging structure, the influence of laser processing conditions both on surface quality and densification level should be considered simultaneously. Fig. 11 gives the surface roughness and porosity rate of overhanging surface using different laser parameters. It can be seen that both insufficient and excessive volume energy density $\omega$ (48 J/mm$^3$ and 120 J/mm$^3$) could result in unfavorable surface roughness (89 $\mu$m and 102 $\mu$m) and relatively large porosity rate (18.3% and 9.5%). Consequently, the optimized processing parameter was identified between 60 and 80 J/mm$^3$. Nevertheless, interestingly, the variation rules of surface quality and densification level with different $\omega$ were exactly converse. As the $\omega$ decreased from 80 J/mm$^3$ to 60 J/mm$^3$, the surface roughness could be reduced from 59 $\mu$m to 33 $\mu$m while the porosity was elevated from 3.2% to 8.4%. In conclusion, in order to improve the surface quality of overhanging surface, the volume energy density should be reduced while the reduction of input energy would lower the densification level of SLM-processed parts. As such, it is urgent to find balanced methods for improving the surface
quality and densification level simultaneously. Based on above thermal physical mechanism analysis and experimental investigation, authors summarize the following solutions which can improve the processability of overhanging structure by SLM:

1. Preheat the substrate to 150 °C before performing the SLM experiment. Substrate preheating enhances the beginning temperature of powder bed and lowers the temperature gradient during SLM process, leading to a reduced surface tension gradient of melt. This can mitigate the capillary instability of melt pool and hence avoid defects in overhanging specimens.

2. Enhance the laser scan speed temperately, meanwhile, in order to guarantee sufficient input energy density, properly reduce the layer thickness. According to above investigation, using a relative large laser scan speed can gain an improved overhanging surface by decreasing the melt pool dimension felicitously. However, higher laser scan speed would lead to the reduction of laser energy density and bring metallurgical defects to SLM parts. Thus, properly reducing the layer thickness when using a high scan speed not only improves the processability of overhanging structure but also guarantee the full density of SLM parts. This method can also effectively alleviate the Staircase effect.

3. Optimize the laser scan strategy: Scan the supported region first and then scan the overhanging region. The supported region solidifies very fast due to the high thermal conductivity of solid materials. When laser scans the powder region, the solidified supported region...
can provide heat-transfer medium for melting overhanging region, hence alleviate the heat accumulation effect in powder region.

(4) Add small amounts of surface-active elements, such as boron and niobium, into original powders. Surface-active elements have the function of reducing surface tension of melt pool during SLM. This is of great help to increase the melt pool stability and improve the processing quality of overhanging structure by SLM.

Fig. 12 gives the intricate lattice structure consisting of numerous overhanging structures fabricated by SLM with the above solutions conducted, showing a high processability of overhanging parts. Besides above strategies, optimizing inclination angle \( \theta \) is also an important method improving the surface quality of overhanging structure. In future studies, the role of inclination angles on the fabrication quality of SLM-processed overhanging structure and the underlying thermal physical mechanism shall be investigated.

5. Conclusion

In this work, a three-dimensional finite volume method (FVM) model was given to study the melt pool thermal behavior during selective laser melting overhanging structure. The SLM experiments were also performed under the same laser processing conditions used in the simulation. The following conclusions can be drawn.

(1) Because of the enormous difference in the thermo-physical properties between as-fabricated part and powder, the maximum operative temperature and the dimension of melt pool obtained in the powder material was typically larger compared to that in the as-fabricated part. An overlarge volume energy density \( \omega \) (120 J/mm\(^3\)) generally led to a large dimension of melt pool, hence giving rise to severe dross formation phenomenon in overhanging structure. Using a considerably low \( \omega \) (48 J/mm\(^3\)) effectively reduced the dimension of melt pool but inhibited the successful fabrication of overhanging part with full density. The optimized volume energy density \( \omega \) was believed to be in the range of 60–80 J/mm\(^3\).

(2) When \( \omega \) was ranged from 60 J/mm\(^3\) to 120 J/mm\(^3\), the velocity vector within the melt pool showed an outward flow pattern. For a relatively low \( \omega \) of 48 J/mm\(^3\), the melt flow exhibited an inward backflow pattern. Various melt flow behaviors caused different final morphologies of overhanging surface.

(3) As the \( \omega \) was set at an overlarge value of 120 J/mm\(^3\), the large thermal-capillary force induced by temperature gradients was inclined to pull the melt away from the center to the periphery of the melt pool and the vector of the velocity field located at the tip of overhanging surface tended to encounter along the overhanging-powder interface. These would result in the severe material stack phenomenon and attendant poor surface quality of overhanging structure. As the \( \omega \) was settled at 48 J/mm\(^3\), melting track would break up into several spherical agglomerates driven by the capillary instability. When \( \omega \) was set at a moderate value ranging from 60 J/mm\(^3\) to 80 J/mm\(^3\), the melt flow behavior was believed to be mild and brought fewer disturbances to the melt pool.

(4) The variation rules of surface quality and densification level with different \( \omega \) (60–80 J/mm\(^3\)) were exactly converse. Four effective methods were summarized to improve the surface quality and densification level of overhanging structure simultaneously: 1) Preheat the substrate to 150 °C before performing the SLM experiment; 2) Enhance the laser scan speed temperately and properly reduce the layer thickness; 3) Optimize the laser scan strategy; 4) Add small amounts of surface-active elements into original powders.

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