Prediction of Primary Dendrite Arm Spacing in Pulsed Laser Surface Melted Single Crystal Superalloy

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Abstract

Primary dendritic arm spacing (PDAS) is an important microstructure feature of the nickel-base single crystal superalloys. In this paper, a numerical model predicting the PDAS evolution with additive manufacturing parameters using pulsed laser is established, which combines the theoretical PDAS models with the temperature field calculation model during pulsed laser process. Based on this model, processing maps that related process parameters to the evolution of PDAS are generated. To obtain more accurate prediction model, the parameters of different solidification conditions, $\bar{G}^{-0.5}\bar{V}^{-0.25}$ and $\bar{G}^{-0.5}\bar{V}^{-0.25}$, are selected to calculate PDAS. The simulation results show that the PDAS increases as the arise of P and t. The processing-PDAS map can accurately predict the evolution of PDAS with pulsed laser process parameters, which is well in accordance with the experimental results. Additionally, the PDAS values calculated by the $\bar{G}^{-0.5}\bar{V}^{-0.25}$ are more in line with the experimental results than those calculated by the $\bar{G}^{-0.5}\bar{V}^{-0.25}$.

Keywords Additive manufacturing · Nickel-base superalloy · Single crystal · Pulsed laser · Primary dendritic arm spacing

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1 Introduction

Additive manufacturing (AM) technology has developed rapidly in the aviation industry in the recent 30 years [1]. The additive manufacturing of metal using laser powder sintering molding [2] is currently the fastest growing research direction [1]. Laser powder sintering molding (LPSM) consists of powder bed-based method [3] and coaxial powder feeding method [4]. Due to their low heat input and high cooling rate, AM technology has many applications in the precise repair and manufacture of nickel-base single crystals (SC) [4–6].

During AM process of SC, columnar-to-equiaxed transition (CET) [7] and crystal orientation evolution [8–10] are critical to a successful repair of SC. All these microstructure phenomena are closely related to the evolution of the solidification condition during this AM process. It is very important to understand the effects of process parameters on the solidification conditions, including cooling rate (R), temperature gradient (G) and dendrite growth rate (V). Thus, many scholars have built numerical calculation models [8, 11–17] to analyze the evolution of solidification conditions of the AM process and further study their effects on solidification microstructural features [15, 18].

Among all the solidification microstructural features, primary dendritic arm spacing (PDAS) is a prominent microstructural feature for SC superalloys. It has an important influence on element segregation and volume fraction of eutectic structure [19], and thus affecting the heat treatment process [19] and mechanical properties of the nickel-base superalloys. There are many factors [19–25] that affect PDAS, such as dendrite growth rate (V), cooling rate (R), temperature gradient (G), local solidification time (t_f) and composition (C_0). In order to make clear the weight index of these factors, lots of theoretical models that describe PDAS were established. Among these models, the most famous ones are Hunt model [24], Kurz–Fisher model [19, 25] and Trivedi model [23]. These models suggest different functional relationships with G and V , but rarely analyze the effect of the cooling rate (R) [19]. According to these models, the PDAS can be expressed as the following form when the tip growth velocity is fast [19, 20, 22, 23, 25, 26].

$$\lambda_1 = cG^{-a}V^{-b} (0 < a, b < 1), \quad (1)$$

where $a=0.5$, $b=0.25$, c is material-dependent parameters.

The calculated PDAS value by the numerical calculation model [27–30] using this equation is in good agreement with the experimental results whether during directionally solidification or during laser process. When solidification conditions (G and V) at different process parameters are calculated, PDAS can be immediately correlated to process parameters, including laser power (P), scanning speed V_s [29].

However, the heat source of those numerical models mentioned above is all about the continuous wave laser. In our previous work, a pulsed laser, instead of a continuous-wave laser, has been successfully applied to fabricate single crystal microstructure, and large size platy samples of single crystal have been obtained [31]. Compared to the continuous laser, the energy output of the pulsed laser is low, consequently a larger temperature gradient in the molten pool can be obtained as the same process condition is selected. Therefore, the pulsed laser is favorable for continuous epitaxial growth of single crystals. However, few numerical calculation models on pulsed laser have been reported.

The purpose of this work is to develop a numerical model that can directly relate the process parameters (power, P , and pulse width, t) of the pulsed laser process to the PDAS of the obtained microstructure. The calculated results of this model will be displayed in the form of processing-PDAS maps as a function of P and t . These maps obtained by the numerical model can be directly used to help control and optimize the laser process.

2 Theoretical Models

2.1 Primary Dendritic Arm Spacing Model

Generally speaking, the PDAS can be described by the dendritic tip radius (R). The dendritic tip radius is determined by the marginal stability of the solid/liquid interface. The evolution of R under different solidification conditions can be expressed as follows [26]:

when the dendrite growth rate (V) is low, $V < \frac{GD}{\Delta T_0 k_0}$,

$$R = \frac{2D}{V(1-k_0)} + \frac{2mc_0}{G}, \quad (2)$$

when V is high, $V > \frac{GD}{\Delta T_0 k_0}$,

$$R = 2\pi \left(\frac{D\Gamma}{\Delta T_0 k_0 V} \right)^{0.5}, \quad (3)$$

where D is the liquid diffusivity, ΔT_0 is the solidification interval, Γ is the Gibbs–Thomson coefficient, G is the temperature gradient, V is the dendrite growth rate, m is the equivalent equilibrium liquidus slope, c_0 is the initial solute content in the liquid and k_0 is the partition coefficient. The DD32 superalloy is regarded as a pseudo-binary alloy Ni-X, the liquidus and solidus are assumed to be straight, and then k_0 can be expressed as follows [32]:

$$k_0 = \frac{(T_m - T_L)}{(T_m - T_S)}, \quad (4)$$

where T_m is the melting point of pure Ni, T_L is the liquidus isotherm, T_S is the solidus isotherm.

When the tip radius of the dendrites is established, the PDAS based on R will also be determined. Kurz and Fisher et al. [25, 26] propose a Kurz–Fisher (KF) model to relate PDAS with R , where the overall morphology of the dendrite is approximated to be an ellipsoid. According to this model, when V is high, λ_1 can be written as:

$$\lambda_1 = 4.3\Delta T'^{0.5} \left[\frac{D\Gamma}{\Delta T_0 k_0} \right]^{0.25} V^{-0.25} G^{-0.5}, \quad (5)$$

where $\Delta T'$ is the difference between the tip temperature and the non-equilibrium solidus isotherm.

For the convenience of calculation, $\Delta T'$, in Eq. (5), is generally replaced by ΔT_0 when $V > \frac{GD}{\Delta T_0 k_0}$ [20] (order of 10^{-5} m/s in this study). Then, λ_1 can be written as:

$$\lambda_1 = 4.3 \left[\frac{\Delta T_0 D\Gamma}{k_0} \right]^{0.25} V^{-0.25} G^{-0.5}. \quad (6)$$

Pulsed laser remelting process in this paper (Fig. 1a) is a local rapid solidification process, and the dendrite

Fig. 1 **a** Schematic diagram of pulse laser remelting process, **b** laser working state, **c** 3D intensity distributions of top hat beam

growth rate V is high [9] and order of 10^{-2} m/s in this study. Therefore, Eq. (6) is selected here to calculate PDAS.

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q. \quad (7)$$

$$q = -k \nabla T. \quad (8)$$

$$Q = \text{sign}(\text{sign}(r_b^2 - r^2) + 1) \text{sign}(\text{sign}(t_1^2 - t^2) + 1) P \eta / \pi r_b^2 + h_c(T_0 - T) + \epsilon \delta_b(T_0^4 - T^4), \quad (9)$$

2.2 Numerical Model of Solidification Conditions

According to Eq. (6), PDAS is correlated to the solidification conditions (G and V). However, the calculation of G and V requires the modeling of temperature field of the pulsed laser process. In this present study, the finite element analysis method is used to establish the modeling of the temperature field of the pulsed laser remelting process. The assumptions of the numerical model are listed as follows:

1. A mathematical model involving heat transfer in laser process is proposed with constant physical properties. Latent-heat release and convection are not considered.
2. The heat loss and the composition loss caused by liquid metal vaporization are ignored.
3. The beam intensity profile of the CO₂ laser, used in the laser process, was a near top hat mode [17], so heat source was set as a near top hat mode, as shown in Fig. 1c.

The conservation equations of the heat transfer are shown in Eqs. (7) and (8). The laser heat flux input is shown in Eq. (9). The boundary conditions are set as $h_c(T_0 - T) + \epsilon \delta_b(T_0^4 - T^4)$. $h_c(T_0 - T)$ stands for natural convection, h_c is the heat transfer coefficient, $\epsilon \delta_b(T_0^4 - T^4)$ stands for the surface to ambient radiation, δ_b is the Stefan–Boltzmann constant, ϵ is the emissivity and T_0 is the ambient temperature

where ρ is the alloy density, c_p is the heat capacity at constant pressure, κ is the thermal conductivity, u is the velocity field defined by the Translational Motion sub-node when parts of the model are moving in the material frame. T is the temperature, t is the processing time, Q is the heat source, t_1 is the pulse width, P is the laser power, η is the laser absorption rate.

2.3 Calculations of the Local Solidification Conditions

The PDAS (λ_1) of a given alloy is mainly determined by the solidification conditions G and V according to Eq. (6). For the pulsed laser process, the evolution of G and V depends on several important laser process parameters, such as P and t . Therefore, the relationship between the solidification conditions (G and V) and pulsed laser process parameters (P and t) should be established. The solidification conditions (G and V) are calculated at the dendrite tip (S/L interface front) because the PDAS is established at dendrite tip. For the convenience of calculation, the dendrite tip is assumed to be given by liquidus isotherm.

Usually, G and V at the S/L interface keep changing with the depth of the solid–liquid interface in the molten pool [4, 7, 12, 16, 17], which affects not only the solidification microstructures, but also the PDAS [4, 32]. Therefore, it is difficult to calculate the PDAS only using G and V . Fortunately, previous

researches have shown that: (1) PDAS will not change during or after solidification if it is established [19]; (2) the PDAS selection criterion during solidification is unique under given G and V , and the dynamics related to the spacing adjustment process are slow [32]; (3) the PDAS selection criterion is not very sharp, and a range of the PDAS is stable under given conditions [32]. Therefore, a reasonable average value of solidification parameters can give calculated results of the PDAS in laser process [27, 29, 33]. The $\bar{G}$ and $\bar{V}$, an average value of over depth $Z_{\max}$, are often used as the solidification parameters in laser process [7, 17, 29].

$$\bar{G} = \frac{1}{|Z_{\max}|} \int_{Z_{\max}}^0 G \cdot dZ. \quad (10)$$

$$\bar{V} = \frac{1}{|Z_{\max}|} \int_{Z_{\max}}^0 V \cdot dZ. \quad (11)$$

It was worth noting that the value of the PDAS at different depths is proportional to $G^{-0.5} V^{-0.25}$ according to Eq. (6), which is also an important characteristic solidification parameter for calculating the PDAS. So, in this study, $G^{-0.5} V^{-0.25}$ (the average value of $G^{-0.5} V^{-0.25}$) was applied to calculate the PDAS, and the calculated results were compared with those that obtained by using the $\bar{G}$ and $\bar{V}$.

$$\overline{G^{-0.5} V^{-0.25}} = \frac{1}{|Z_{\max}|} \int_{Z_{\max}}^0 G^{-0.5} V^{-0.25} \cdot dZ. \quad (12)$$

3 Experimental

To study and verify the effect of the process parameters of pulsed laser on the PDAS, laser remelting experiments were carried out under different process conditions with a laser beam of 2.2 mm in diameter. The schematic diagram of the pulse laser remelting process is shown in Fig. 1. The pulsed laser does not move when it emits light, so the liquidus isotherm of the molten pool and the bottom of the mushy zone are close to round. Pulse energy (P) and pulse width (t) are the main process parameters (Fig. 1b). The detailed processing parameters, molten pool diameter and the PDAS results are listed in Table 1.

DD32, a nickel-base single crystal (SC) superalloy, was used as the substrate. The nominal composition of DD32 is shown in Table 2. Thermal properties used for the finite element simulation are shown in Table 3. The substrate used for the laser remelting process was exposed to fully heat-treated: 1280 °C × 4 h/AC + 1290 °C × 4 h/AC + 1150 °C × 4 h/AC + 870 °C × 24 h/AC and the primary arm dendrite of the substrate is perpendicular to the remelting surface. Before the laser remelting experiment, all the surface of the substrate was polished with 150 grit sandpaper and washed with absolute ethanol. Each experiment was repeated three times.

All these melted samples were polished and etched with a corrosive solution consisting of 20 g CuSO₄+100 ml HCl+5 ml H₂SO₄+80 ml H₂O. The microstructures of the remelted samples were characterized by optical microscopy (OM: Axio Observer 3 m). The PDAS was calculated according to the relationship $\lambda_1 = (A/N)^{0.5}$, where A the area

Table 1 Processing parameters (laser power, P , pulse width, t and beam diameter, D_b) and the corresponding calculated and measured diameters of molten pool, D_c and D_m , and primary dendritic arm spacing, λ_1

No	t , s	P , W	Pt , J	D_b , μm	D_c , μm	D_m , μm	λ_1 , μm
A	0.1	1800	180	2200	1416	1399	3.2 ± 0.45
B	0.1	2200	220	2200	1857	1902	3.7 ± 0.45
C	0.1	2600	260	2200	2054	2305	4.3 ± 0.50
D	0.16	1800	288	2200	1712	2145	4.3 ± 0.55
E	0.16	2200	352	2200	2020	2353	4.6 ± 0.65
F	0.16	2600	416	2200	2159	2558	5.8 ± 0.75
G	0.22	1800	396	2200	1853	2405	4.8 ± 0.60
H	0.22	2200	484	2200	2102	2564	5.2 ± 0.65
I	0.22	2600	572	2200	2205	2743	6.0 ± 0.75
J	0.28	1800	504	2200	1936	2376	5.6 ± 0.65
K	0.28	2200	616	2200	2149	2678	6.0 ± 0.70
L	0.28	2600	728	2200	2242	2827	6.9 ± 0.75

Table 2 Main chemical composition of DD32 alloy (mass fraction, %)

C	Cr	Co	W	Mo	Al	Nb	Ta	Re	Ni
0.12–0.18	4.30–5.60	8.00–10.00	7.70–9.50	0.80–1.40	5.60–6.30	1.40–1.80	3.50–4.50	3.50–4.50	Bal

Table 3 Thermophysical properties of the DD32 SC alloy used for calculation of PDAS

Properties	Values
Melting point of pure Ni, T_m	1726 (K)
Solidification interval, ΔT_0	39.3 (K)
Absorption coefficient, η	0.12
Emissivity, ϵ	0.7
Ambient temperature, T_0	293.15 (K)
Partition coefficient, k_0	0.62
Gibbs–Thomson coefficient, Γ	1.8×10^{-7} (m K)
Liquid diffusivity, D	3×10^{-9} (m ² /s)
Solid density, ρ_s	8550 (kg/m ³)
Liquid density, ρ_L	8550 (kg/m ³)
Solidus temperature, T_s	1621.7 (K)
Liquidus temperature, T_l	1661 (K)
Solid specific heat, Cp_s	550 (J kg ⁻¹ K ⁻¹)
Liquid specific heat, Cp_l	550 (J kg ⁻¹ K ⁻¹)
Solid thermal conductivity, k_s	22 (W m ⁻¹ K ⁻¹)
Liquid thermal conductivity, k_l	22 (W m ⁻¹ K ⁻¹)

measured by the Image-Pro Plus software, N is the number of dendrites in the area [34]. Both the calculated and the experimental PDAS are displayed in the form of processing-PDAS maps as a function of P and t . To obtain the processing-PDAS maps with smooth contour lines, the PDAS data under different process conditions were converted to matrix using random gridding method.

4 Results

4.1 Microstructure Features of the Molten Pool

Figure 2 shows the OM image of the molten pool. As can be seen, the solidification microstructure elevates from planar to dendritic which grows epitaxially from the SC substrate along [001] crystallographic at the center of the molten pool. On the left and right sides of the molten pool, the columnar dendrites orientation changes from [001] to [100] and

[010], respectively. At the top of the molten pool, a small number of stray grains form. These microstructure features are similar to the results of previous continuous laser process research [2–4, 8]. Generally, the maximum temperature gradient direction of <001> crystal orientation is the growth direction of the dendrite, and the microstructure features are the results of changing in the max temperature gradient ($G_{[100]}$, $G_{[010]}$, $G_{[001]}$). Detailed calculations are shown in reference [4]. Because dendritic epitaxial growth is along the [001] direction at the center of the molten pool, we mainly focus on $G_{[001]}$ and $V_{[001]}$. To predict the PDAS, the stray grain is ignored.

4.2 Solidification Variables of the Molten Pool

Figure 3 shows the calculated evolution of local solidification variables ($G_{[001]}$ and $V_{[001]}$) with the increase of Z at the S/L interface of the center position of the molten pool under the condition of 1800 W, 0.1 s. It can be seen that as Z increases, $G_{[001]}$ tends to reduce which reaches a minimum at the top of the molten pool, but $V_{[001]}$ is the

Fig. 3 Evolution of the $G_{[001]}$ and $V_{[001]}$ with the increase of Z at the S/L interface of the center position of the molten pool under the condition of 2600 W, 0.1 s

Fig. 2 Solidification microstructure of the cross section of the molten pool. The green dotted line is the dividing line between different growth directions. The area between the red dotted lines in the orange magnification area is planar interface

reverse, its value is close to zero at the initial position and then increases with increasing depth. The decrease of $G_{[001]}$ is fast at the initial solidification process, but slow at the later solidification process. The increase of $V_{[001]}$ is slow at the initial solidification process, but fast in the late solidification. Changes in $G_{[001]}$ and $V_{[001]}$ will increase the difficulty of predicting the PDAS. Thus, it is important to choose the appropriate characteristic solidification conditions to describe the relationship between PDAS and solidification parameters.

4.3 Effects of $\bar{G}^{-0.5}\bar{V}^{-0.25}$ and $\overline{G^{-0.5}V^{-0.25}}$ on PDAS

The different characteristic solidification conditions, $\bar{G}^{-0.5}\bar{V}^{-0.25}$ and $\overline{G^{-0.5}V^{-0.25}}$, of the molten pool were chosen to calculate the PDAS in this present study. A comparison between the processing-PDAS maps evaluated by the two conditions can contribute to select more appropriate characteristic conditions.

To visualize the effect of the two conditions on PDAS, the effects of P , t and the two conditions on PDAS are studied. The calculated results are shown in Fig. 4a and b. The PDAS values evaluated by $\bar{G}^{-0.5}\bar{V}^{-0.25}$ and $\overline{G^{-0.5}V^{-0.25}}$ are drawn as contour maps, which are a function of P and t . As can be seen in Fig. 4a and b, the influence of P and t on the calculated PDAS is simple. The calculated PDAS values increase with the increase of P and t . In other words, increased heat input (Pt) leads to larger PDAS. The contours shape of the two processing-PDAS maps is similar. However, the PDAS values calculated by $\overline{G^{-0.5}V^{-0.25}}$ are higher than that calculated by $\bar{G}^{-0.5}\bar{V}^{-0.25}$. Further experiments are needed to verify which result is closer to the actual value.

4.4 Experimental verification

Figure 5a shows dendritic morphologies in the cross section of the molten pool under different process conditions. At low P and t , the primary dendrite arm is small, and the secondary dendrite arm is not well developed. At high P and t , the primary dendrite arm is big, and the secondary dendrite arm is well developed. Figure 5b shows the histogram of PDAS at different conditions. At low P and t , the PDAS is small. At high P and t , the PDAS is big. The PDAS increases with the rise of P and t . It can be seen from Table 1 that the PDAS increases with the increase of heat input (Pt). Accordingly, low heat input always contributes to small PDAS, which agrees well with the calculated results.

In order to visually compare the calculated PDAS values with the experimental PDAS values, the calculated and the experimental PDAS values are shown in Fig. 6. As can be seen in Fig. 6, both two calculation results can well characterize the variation trend of the PDAS with the increase of P and t although there is a certain difference between the calculated value and the experimental value. At low P and t , the contour value of PDAS calculated by $\bar{G}^{-0.5}\bar{V}^{-0.25}$ is a little higher than the experimental one, and the contour value of PDAS calculated by $\bar{G}^{-0.5}\bar{V}^{-0.25}$ is a little lower than the experimental one. At high P and t , the contour value of PDAS calculated by $\overline{G^{-0.5}V^{-0.25}}$ is a little lower than the experimental one, while the contour value of PDAS calculated by $\bar{G}^{-0.5}\bar{V}^{-0.25}$ is much lower than the experimental one. Overall, the contour value of PDAS calculated by $\overline{G^{-0.5}V^{-0.25}}$ is closer to the experimental value.

Correlation between the experimental PDAS value and these calculated ones is shown in Fig. 7. The variation trends of the PDAS with t at different powers are shown in Fig. 8. As can be seen from Fig. 7, both calculated PDAS values

Fig. 4 Combined effects of P , t and two characteristic solidification conditions on the PDAS (in μm): **a** evaluated by using the $\bar{G}^{-0.5}\bar{V}^{-0.25}$, **b** evaluated by using the $\overline{G^{-0.5}V^{-0.25}}$

Fig. 5 **a** Dendritic morphologies in the transverse section of the molten pool made under different processing conditions, **b** the histogram of PDAS

Fig. 6 Comparison of the contour map on the PDAS (in μm) between the experimental results and those calculated

can accurately capture the trend of the experimental PDAS variation, and the fitting results show that the λ_1 calculated by $G^{-0.5} V^{-0.25}$ are more in line with the results of the experimental λ_1 . As can be seen from Fig. 8, the calculated PDAS values at low t slightly overestimate the PDAS, while underestimate the PDAS for a relatively high t , especially at high powers (such as 2600 W), and the underestimation is obvious with the rise of t . That is to say, the calculated PDAS is

Fig. 7 Correlation between the experimental PDAS and those calculated

well fitted with the experimental PDAS at a low heat input. A similar result is reported in other research [28]. Although the calculated PDAS using different solidification conditions have certain differences with the experimental PDAS, using $G^{-0.5} V^{-0.25}$ can get a better match between the calculated and the experimental results.

Fig. 8 Variation trends of the PDAS with t at different powers

Fig. 9 Evolution of the G/V as a function of Z under the condition of 2600 W, 0.1 s

5 Discussion

5.1 Microstructure of the Molten Pool

The solidification microstructure at the bottom is planar and then evolves from planar to dendritic. According to the solidification structure of the single-phase alloy at very slow solidification rates [19], the high-temperature gradient will induce the formation of planar structure. This can be explained by the theory of constitutional supercooling [18, 31]. Figure 9 shows the evolution of the G/V as a function of Z . The G/V value decreases as Z increases. According to the constitutional supercooling theory [19, 31], when the $G/V > \Delta T_0/D$ (in this paper the

$\Delta T_0/D = 1.3 \times 10^{10}$), the solid–liquid interface is stable and planar solidification interface forms. Obviously, the G/V value at the bottom of the molten pool is greater than the value of $\Delta T_0/D$ in this work, and therefore planar solidification interface will appear (shown in Fig. 2) at the bottom of the molten pool, similar to other reports [12]. Then, as the ratio of G/V decreases, the S/L interface becomes unstable. Columnar/cell crystals are formed with further solidification, and at the same time, PDAS is established.

5.2 Influence of the Pulsed Laser Parameters on PDAS

The PDAS of a given alloy value is mainly determined by the solidification conditions G and V . Thus, understanding the relationship between the solidification conditions ($\bar{G}$ and $\bar{V}$) and process parameters is of great significance for understanding the influence of the pulsed laser parameters on PDAS.

Figure 10 shows contour maps of the influences of laser power, P , and pulse width, t , on the $\bar{G}$ and $\bar{V}$ values. The $\bar{G}$ and $\bar{V}$ values are mapped as a function of P and t . The influence of P and t on the $\bar{G}$ and $\bar{V}$ is very complicated. It is not possible to express them with a simple formula. For a given P , the $\bar{G}$ and $\bar{V}$ all monotonically decrease with increasing t . For a given t , the $\bar{V}$ decreases significantly with increasing P . It indicates that low heat input induces high $\bar{G}$ and $\bar{V}$, which is similar to previous researches [4, 29]. Because the functional relationship between λ_1 , G and V was described as: $\lambda_1 \propto G^{-0.5}V^{-0.25}$, the increase of P and t will lead to an increase in the PDAS. $\bar{G}$ declines about 31% and $\bar{V}$ declines about 25%. According to $\lambda_1 \propto G^{-0.5}V^{-0.25}$, the effect of $\bar{G}$ value on the variation

Fig. 10 Contour maps showing the influences of laser power, P , and pulse width, t , on the (a) $\bar{G}$ (K/m) and (b) $\bar{V}$ (m/s) values

trend of PDAS is more than that of $\bar{V}$ value. So, the shape of the contour lines in the processing-PDAS map is similar to that of P - t - $\bar{G}$ map.

5.3 Difference Between the Calculated and the Experimental PDAS Results

Overall, the calculated PDASs agree well with the experimental PDASs. However, due to the simplifying assumptions of the model, there are still inevitable differences between the calculated and the experimental values like previous research [27, 29, 35].

For the numerical model, latent-heat release and fluid flow are neglected, and some physical properties are set as constant. The liquidus isotherm is assumed to give the shape of the molten pool, which deviates from the experimental molten pool morphology. And the latent heat of phase transition is ignored. For the PDAS model, $\Delta T'$, in Eq. (5), is replaced by ΔT_0 , k_0 is obtained by assuming the liquidus and the solidus isotherms are straight. The liquidus is obtained by the equilibrium phase diagram, and the G value is calculated just at the liquidus while the temperature gradient of the solid phase is ignored. What is more, the effect of fluid convection, especially Marangoni convection, on the temperature gradient of the molten pool is completely ignored.

Previous researches [36, 37] have shown that natural convection rates are the order of 1 mm/s while Marangoni convection rates are the order of 1 m/s. The Marangoni convection in the liquid pool determines the shape of the molten pool and greatly affects the thermal field [36, 38]. Drezet et al. [36] found that the Marangoni convection becomes visible when the molten pool is larger than the beam diameter.

The calculated and measured diameters of the molten pool are shown in Table 1. As can be seen, the diameter of the molten pool increases with the rise of heat input. The diameter of the molten pool is larger than the laser beam diameter under high heat input conditions. Thus, the Marangoni convection gradually increases with the rise of the heat input. This is why the variation of PDAS between the experimental and calculated under high heat input conditions is significant than that under low heat input conditions.

Although there are still differences between the calculated and the experimental values, the variation trends of the calculated PDAS with the processing parameter, laser power P and pulse width t , in the processing-PDAS map can express the actual PDAS variation trends, and the processing-PDAS map obtained by the numerical model is useful for controlling and optimizing the LMF process.

6 Summary and Conclusions

This study has developed a numerical model of PDAS for Ni-base SC superalloys when melted by pulsed laser process. The numerical model related the theoretical PDAS model with the temperature field calculations model. Based on this model, the calculated PDASs are in good agreement with the experimental PDASs. To obtain more appropriate characteristic conditions, comparison of the effect of $\bar{G}^{-0.5} \bar{V}^{-0.25}$ and $\bar{G}^{-0.5} \bar{V}^{-0.25}$ on PDAS is studied. The following conclusions can be drawn from this work.

1. The PDAS increases as the rise of P and t .
2. The $\bar{G}$ and $\bar{V}$ increase with the rise of P and t .

3. The PDAS values calculated by the $\overline{G^{-0.5}V^{-0.25}}$ are more in line with actual PDAS values than those calculated by the $\bar{G}^{-0.5}\bar{V}^{-0.25}$.

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