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Prediction of primary dendritic arm spacing during laser rapid directional solidification of single-crystal nickel-base superalloys

Yao-Jian Liang [a, b, c], An Li [a, b, c, *], Xu Cheng [a, b, c], Xiao-Tong Pang [a, b, c], Hua-Ming Wang [a, b, c]

[a] National Engineering Laboratory of Additive Manufacturing for Large Metallic Components, Beihang University, 37 Xueyuan Road, Beijing 100191, People's Republic of China

[b] Engineering Research Center of Ministry of Education on Laser Direct Manufacturing for Large Metallic Components, Beihang University, 37 Xueyuan Road, Beijing 100191, People's Republic of China

[c] School of Materials Science and Engineering, Beihang University, 37 Xueyuan Road, Beijing 100191, People's Republic of China

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ABSTRACT

Primary dendritic arm spacing (PDAS) is an important microstructure feature in the nickel-base single-crystal (SX) superalloys by laser rapid directional solidification (LRDS). A combined numerical model was developed in this paper to investigate the influence of laser processing parameters on the PDAS. This model consists of (1) the theoretical PDAS models which relate PDAS to the solidification conditions and (2) the heat-flux calculations of laser processing which provide the solidification conditions as a function of the processing parameters. It is therefore able to immediately relate the PDAS to the processing parameters and obtain corresponding processing–microstructure maps. To verify the predicted accuracy, the PDAS values calculated by different theoretical models were compared with those produced under different processing conditions. Results show that the PDAS firstly decreases and then increases at a lower laser power whereas it decreases with increasing scanning velocity at a higher laser power, leading to nose-shape contour lines. The predicted accuracy depends on appropriate selections of material thermo-physical properties. These processing–microstructure maps can accurately capture the trends of the PDAS variation with the processing parameters and contribute to the control and optimization of dendritic microstructure while determining relevant processing windows for controlled SX laser processing.

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1. Introduction

Nickel-base single-crystal (SX) superalloys are unique high-temperature materials used as turbine blades and vanes due to their excellent mechanical properties at elevated temperatures [1,2]. Nevertheless, many types of damage, *e.g.*, blade tip erosion, are unavoidable under high temperature conditions. This means that the repair of damaged SX components is necessary because of the extremely high replacement costs. Laser processing, *e.g.*, laser additive manufacturing (LAM), is particularly suitable for precise repair and fabrication of these SX components because it allows rapid and accurate addition of controlled amounts of material to required locations with low heat input and high cooling rate [3–6].

Successful SX laser processing needs to ensure the columnar dendrites epitaxially growing from the substrate and suppress the nucleation and growth of equiaxed grains in the constitutional supercooling (CS) region ahead of the solid/liquid (S/L) interface, *i.e.*, columnar-to-equiaxed transition (CET). Therefore, numerous studies have focused on the solidification behavior of the laser-processed SX alloys [7–22]. All these studies have contributed to the successful SX laser processing and good agreements were obtained between the predicted and experimental results. However, in addition to the CET and dendritic growth pattern, primary dendritic arm spacing (PDAS) is another remarkable microstructure feature in these laser-processed SX superalloys. It affects the segregation behavior as well as the precipitation of secondary phases within interdendritic regions, which subsequently influences the mechanical properties of SX superalloys. Therefore,

* Corresponding author. National Engineering Laboratory of Additive Manufacturing for Large Metallic Components, Beihang University, 37 Xueyuan Road, Beijing 100191, People's Republic of China.
E-mail address: li_an@buaa.edu.cn (A. Li).

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many researchers have attempted to understand the relationship between solidification conditions and PDAS [23–30]. Of reported theoretical models, almost PDAS models present a common characteristic especially when the dendritic growth velocity is high. This general formula is [25–30]:

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

where λ_1 is the PDAS, a, b, and N are material-dependent parameters, G is the temperature gradient and V is the dendritic growth velocity. Generally, $a = 0.5$ and $b = 0.25$ [25–29]. By using the two values, good agreement can be obtained in directionally solidified (DS) superalloys [29,31,32] though those models were established based on simple binary-alloy systems.

Although the effects of the solidification conditions on the PDAS in conventional DS process have been extensively investigated, those in laser processing are limited. Acharya et al. [18] first incorporated Eq. (1) in the scanning laser epitaxy (SLE) process to simultaneously determine the PDAS when the solidification morphology, *e.g.*, CET, was estimated under various solidification conditions. More importantly, owing to high G and V, the epitaxial dendrites in the SX alloys produced by laser rapid directional solidification (LRDS) (or SLE) process are rather fine(~10–30 μm) [18] compared with conventional DS process, which indicates that the microsegregation can be controlled by decreasing the PDAS. Therefore, the understanding of the processing–PDAS relationship during the LRDS process contributes to select a SX processing window with fine PDAS and, further improve properties of SX alloys. However, their research did not establish a direct relationship between laser processing parameters and PDAS, which limited the application of their conclusions to the actual laser processing because the processing–solidification condition relationship is also complex.

It is noteworthy that the research by Gäumann et al. [20,21] presented some processing–microstructure maps that *immediately* relate several crucial processing parameters (including laser power, P, scanning velocity, V_b, beam diameter, D_b, and preheating temperature, T_0) to solidification morphology by using a numerical model consisting of their CET criterion [33] and the heat-flux calculation of laser processing. These maps allow to predict the processing windows for directional dendritic growth, which implies that the PDAS can also be *immediately* related to the processing parameters by developing a similar combined model. By this way, the PDAS can be simultaneously controlled and optimized while determining relevant SX processing windows. With this in mind, such a model will be excellent extension and supplement of earlier work by Gäumann et al. [20,21]. In particular, such a combined numerical model can easily collect abundant predicted results under a large number of sets of processing parameters, which is more suitable to obtain the processing maps that require numerous data in comparison to finite element models.

The main objective of this work is to develop a numerical model that can directly relate the PDAS to the processing parameters. The predicted results were shown in the form of processing–microstructure maps. Additionally, the influence of laser processing parameters on the PDAS was investigated according to these processing maps. To verify the predicted accuracy, laser remelting experiments were conducted to obtain various LRDS conditions and the resulting PDAS values were compared with those predicted by the map. Such processing–microstructure maps contribute to the control and optimization of dendritic microstructure while determining relevant processing windows for controlled SX laser processing.

2. Theoretical models

For immediately relating the PDAS to the processing parameters, a combined numerical model developed here consists of (1) the theoretical PDAS models which relate the PDAS to the solidification conditions and (2) the heat-flux calculations of laser processing which provide the solidification conditions as a function of the processing parameters.

2.1. Primary dendritic arm spacing models

Prediction of the PDAS requires the modeling of the relationship between material systems and solidification conditions. Among the PDAS models mentioned previously, most models present a common form, *i.e.*, Eq. (1), when the V is high. Thus, the trends of the PDAS variation with $G^{-1/2}V^{-1/4}$ calculated by these models should be similar. Furthermore, sufficient accuracy can be obtained when $a = 0.5$ and $b = 0.25$ [29,33]. Therefore, the Kurz–Fisher (KF) model, a common and effective model, was selected here on behalf of Eq. (1) to calculate the PDAS.

Under a constrained growth condition like the LRDS process, the dendrites are constrained to adapt to the corresponding tip undercooling, which is determined by the tip solute flux [25]. By assuming the fully developed dendrites to be an ellipsoid of revolution [26] and the conditions of marginal stability, a relationship of the solidification conditions to the PDAS can be written as [25,26]:

$$\lambda_1 = 4.3 \cdot \left(\frac{\Delta T_0 \cdot D \cdot \Gamma}{k_0}\right)^{\frac{1}{4}} \cdot G^{-\frac{1}{2}} \cdot V^{-\frac{1}{4}} \tag{2}$$

where ΔT_0 is the solidification interval, D is the liquid diffusivity, Γ is the Gibbs–Thomson coefficient, and k_0 is the partition coefficient.

Different from the KF model which requires *a priori* assumptions, Hunt and Lu [23,24] proposed fully self-consistent solutions for axisymmetric interface shapes using time-dependent finite-difference models of solute transport, which were incorporated into the spacing selection mechanism. By fitting the numerical solutions, they suggested an analytical expression, the HL model, which is easy to compare theoretical with experimental results. The analytical relationship of the numerical results is [24]:

$$\lambda_1' = 0.07798 \cdot V'^{(a-0.75)} \cdot (V' - G')^{0.75} \cdot G'^{-0.6028} \tag{3}$$

where:

$$\lambda_1' = \frac{\lambda_1 \Delta T_0}{\Gamma k_0},\ G' = \frac{G \Gamma k_0}{\Delta T_0^2},\ V' = \frac{V \Gamma k_0}{D \Delta T_0} \tag{4}$$

and a is given by:

$$a = -1.131 - 0.1555 \log_{10}(G') - 0.007589[\log_{10}(G')]^2 \tag{5}$$

Since the λ_1 calculated by the HL model refers to the radius rather than the more commonly measured diameter, its values need to be multiplied by 2–4 for comparison with the KF model and measured PDAS values.

2.2. Calculations of the local solidification conditions

For a given alloy, the solidification conditions (G and V) determine the PDAS. However, if one needs to relate immediately the processing parameters to the PDAS, a relationship between the G and V and the processing parameters is also necessary. For the laser processing, several important processing parameters, including P,

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