Materials & Design 130 (2017) 197–207

Contents lists available at ScienceDirect

Materials & Design

journal homepage: www.elsevier.com/locate/matdes

Microstructural control during laser additive manufacturing of single-crystal nickel-base superalloys: New processing–microstructure maps involving powder feeding

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ARTICLE INFO

Keywords:
Laser additive manufacturing
Nickel-base superalloys
Processing
Epitaxial growth
Solidification microstructure

ABSTRACT

The control of solidification microstructure is critical to successful laser processing of single-crystal (SX) nickel-base superalloys and a practical tool for the microstructural control is processing–microstructure maps. However, the maps presented in literature do not consider the effects of powder feeding during laser additive manufacturing (LAM) of SX superalloys. This paper therefore presents a simple and feasible strategy to deal with the effects of powder feeding and to extend the combined numerical model used to calculate processing–microstructure maps. A characteristic ratio of epitaxial SX growth was defined to quantitatively compare the final solidification microstructure. Resulting processing–microstructure maps can estimate the influence of most processing variables, especially powder feeding rate, on the extent of epitaxial SX growth and the position of columnar-to-equiaxed transition. Using the processing parameters selected according to these processing–microstructure maps, a multi-layer SX deposit with fine dendrites was successfully fabricated by LAM. This successful SX LAM indicates that these new processing–microstructure maps involving powder feeding are reliable and useful because they can determine proper processing windows for LAM of SX superalloys and further advance the understanding of the processing–microstructure relationship in powder-feeding LAM process.

1. Introduction

Single-crystal (SX) nickel-base superalloys have been widely used to manufacture the turbine blades in advanced aero-engines due to their excellent high-temperature properties [1,2]. Nevertheless, many types of damage to these SX components, *e.g.*, blade tip erosion, are unavoidable under high-temperature and high-pressure conditions. Because of the extremely high replacement costs, it is desirable to be able to repair these damaged SX components. A feasible repair technique is laser processing, especially laser additive manufacturing (LAM), because it allows the addition of controlled amounts of material to required locations and can provide high temperature gradients and cooling rates [3–8]. To ensure the SX solidification during laser processing, it is necessary to understand the relationship between the processing conditions and the solidification microstructure.

A large amount of research on the solidification behavior of laser-processed SX alloys [9–20] has demonstrated that the achievement of successful SX laser processing needs to suppress the nucleation and growth of stray grains (SGs) in the constitutional supercooling (CS) region, *i.e.*, columnar-to-equiaxed transition (CET), ahead of the solid–liquid (SL) interface. To quantitatively investigate this crucial phenomenon common in solidification, Hunt [21] developed the first analytical CET model for casting process based on the growth competition between columnar dendrites and new equiaxed grains formed ahead of the SL interface. Gäumann et al. [22] subsequently extended this CET model to rapid solidification conditions by using the Kurz–Giovanola–Trivedi model [23] to evaluate the CS region of rapid dendritic growth. To easily relate CET to the solidification conditions, a simplified CET criterion for complex multicomponent alloys was further derived [9]:

$$G^n/V = K \tag{1}$$

where G is the temperature gradient, V is the dendritic growth velocity, n and K are material-dependent constants. When the G^n/V ratio is less than K, CET will occur. This CET criterion indicates that the direct relationship between the processing conditions and the solidification microstructure can be established, provided that the solidification conditions are evaluated.

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http://dx.doi.org/10.1016/j.matdes.2017.05.066
Received 27 January 2017; Received in revised form 16 May 2017; Accepted 23 May 2017

To obtain the direct processing–microstructure relationship, Gäumann et al. [9] incorporated the CET criterion into a laser-remelted heat-transfer model that can evaluate the solidification conditions as functions of the processing parameters. The depth-weighted average of G^n/V along the centerline of the SL interface was calculated to rapidly estimate the microstructure based on Eq. (1). The resulting processing–microstructure maps can directly relate the final microstructure (SX or polycrystalline) to several important processing parameters (laser power P, scanning velocity V_b, beam diameter D_b, and preheating temperature T_0). In particular, these maps will be a practical tool for the microstructural control because they can predict the required SX-processing windows and improve the understanding of the processing–-microstructure relationship during SX laser processing.

However, the mean G^n/V ratios used by Gäumann et al. [9] are difficult to effectively characterize the actual CET ahead of the entire SL interface because G and V are functions of the position at the SL interface. Vitek [10] therefore investigated the variation trends of the local SG volume fraction ϕ with the position of the calculated SL interface using a combined model consisting of a simple analytical heat-transfer model and the CET criterion. The area-weighted averages of ϕ were calculated to obtain the processing maps that show the influence of the processing parameters and the substrate orientation on SG formation. From these processing maps, it was found that the local SG fraction relates to both the processing parameters and the substrate orientation, whereas the overall SG fraction depends mainly on the processing conditions. These conclusions were subsequently verified by Anderson et al. [13,14] based on a more accurate model involving heat-transfer and fluid-flow calculations. They further found that the highest SG formation trend occurs at the positions where different preferred orientations intersect. This finding presents a possibility to control the trend of CET by reducing such intersections and has been confirmed in the subsequent work by Wang et al. [15].

Although the above results, especially the processing maps [9,10], have contributed to the understanding of the processing–microstructure relationship during SX laser processing, these studies were performed based on the modeling of laser remelting/welding *without* powder feeding. This may lead to the deviation from the actual LAM process *with* powder feeding. One strategy to reduce this deviation is to develop more accurate models such as finite element models (FEMs) that can simultaneously deal with heat/mass transfer, convection, free surface flows, and especially the effect of powder. Acharya et al. [16,17] presented a coupled thermal, fluid flow, and microstructure model for a powder-bed-based LAM (*i.e.*, scanning laser epitaxy) process. Their results revealed the effect of convection and powder on the melt-pool geometries, the mushy zone sizes, and the CET positions. In addition, Liu and Qi [18] developed a multi-physical model for a powder-feeding LAM (*i.e.*, laser powder deposition) process to study the microstructure formation under various substrate orientations. Similar to previous research without considering powder feeding [10–15], their work also showed that the variations in the substrate orientations in the melt-pool longitudinal sections mainly affects the CET positions, whereas the variations in the transverse sections mostly alters the preferred growth directions. These results imply that powder feeding appears to have no significant influence on overall crystal growth patterns though it can change the positions where CET takes place.

Compared with the analytical heat-transfer models used to calculate the processing maps [9,10], the above advanced FEMs [16–18] are closer to actual cases. However, these FEMs are not suitable for the calculation of the processing maps that require numerous data regarding the relationship between the processing parameters and the microstructure, because the computation of the FEMs is generally time-consuming. Moreover, although the processing maps reported in literature do not consider the effect of powder feeding, they have many unique and attractive advantages. For instance, they can visually present the effect of each processing variable on the microstructure formation so that the appropriate adjustment of the processing parameters is easy to be performed during actual SX laser processing/LAM. Therefore, it is desirable to obtain the new processing–microstructure maps involving powder feeding. This requires a new strategy to deal with the effects of powder feeding in the relevant analytical models used to calculate these maps.

In this work, a simple and feasible strategy that can deal with the effect of powder feeding was presented to extend the combined numerical model used to calculate the new processing–microstructure maps. This combined model consists of (1) an analytical heat-transfer model that uses the laser processing parameters to calculate the solidification conditions and (2) a microstructure selection model that relates the calculated solidification conditions to the microstructure. Consequently, it can directly relate the processing parameters to the solidification microstructure in the form of processing–microstructure maps. A characteristic ratio of epitaxial SX growth was also defined to quantitatively compare the final solidification microstructure. These maps involving powder feeding are useful because they can determine proper SX-processing windows and further advance the understanding of processing–microstructure relationship in power-feeding LAM process.

2. Theoretical models

2.1. Calculation of solidification conditions

For LAM, the processing parameters govern the solidification conditions (G and V) and affect the solidification behavior. An analytical heat-transfer model based on laser remelting was therefore selected to evaluate G and V as functions of the processing parameters, and to rapidly collect abundant predicted data required for the processing maps. However, such a model cannot involve powder feeding rate m, which is an important processing variable affecting the microstructure formation in powder-feeding LAM process. Therefore, this heat-transfer model must be extended to take the effects of powder feeding into account and to improve the accuracy of the model (see Section 2.3 in detail). More details regarding the heat-transfer modeling and the calculation of G and V can be obtained elsewhere [9,20].

2.2. Evaluation of solidification microstructure

Evaluation of the microstructure formation and epitaxial SX growth in LAM process requires a microstructure selection model that can estimate whether CET occurs or not. The most recent model proposed by Gäumann et al. [9,22] is given by:

$$G = \frac{1}{n+1}\cdot\sqrt[3]{\frac{-4\pi N_0}{3\ln(1-\phi)}}\left(1-\frac{\Delta T_n^{n+1}}{\Delta T_{tip}^{n+1}}\right)\Delta T_{tip} \tag{2}$$

where N_0 is the number of nucleation sites (nuclei density), ΔT_n is the nucleation undercooling, and ΔT_{tip} is the dendritic tip undercooling. To rapidly evaluate ΔT_{tip} under different growth conditions, Gäumann et al. [9] fitted the variation of ΔT_{tip} with V by a simple expression $(aV)^{1/n}$ (where a is a material parameter), and proposed that $a = 1.25 \times 10^6$ ($K^{3.4}/m{\cdot}s$) and $n = 3.4$ for CMSX-4 SX alloy. Moreover, in a first approximation of Eq. (2), ΔT_{tip} is proportional to the solidification interval, ΔT_0, and given by [24]:

$$\Delta T_{tip} = (aV)^{1/n} = \Delta T_0\cdot(bV)^{1/n} \tag{3}$$

where b is a material parameter. According to our previous work [19], the a value calculated by Eq. (3) is 1.55×10^5 ($K^{3.4}/m{\cdot}s$) for the alloy used here. Under high temperature gradients, N_0 plays the important role and ΔT_n can be reasonably neglected [9,21,22]. As a result, Eq. (2) can be simplified and a criterion based on the G^n/V ratio can be derived to estimate the solidification microstructure: