Journal of Materials Science & Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Effect of substrate preset temperature on crystal growth and microstructure formation in laser powder deposition of single-crystal superalloy

Zhaoyang Liu[a,b,*], Zi Wang[c]

[a] College of Innovation and Entrepreneurship, Southern University of Science and Technology, Shenzhen 518055, China
[b] Shenzhen Key Laboratory for Additive Manufacturing of High Performance Materials, Southern University of Science and Technology, Shenzhen 518055, China
[c] State Key Laboratory of Powder Metallurgy, Central South University, Changsha 410083, China

ARTICLE INFO

Article history:
Received 19 December 2017
Received in revised form 19 January 2018
Accepted 4 April 2018
Available online xxx

Keywords:
Single-crystal superalloy
Crystal growth
Laser powder deposition

ABSTRACT

A successful repair of single-crystal components needs to avoid the stray grain formation and achieves continuous epitaxial growth of columnar dendrites in the repaired zone. In this study, the effect of substrate preset temperature on crystal growth and microstructure formation in laser powder deposition of single-crystal superalloy was studied through an improved mathematical model and corresponding experimental approaches. The results indicated that the variation of substrate preset temperature between −30 °C and +210 °C changes the molten pool morphology little, but obviously affects the columnar-to-equiaxed transition conditions. The preheating of substrate facilitates the stray grain formation and enlarges the primary columnar dendrite arm spacing, while the situation for precooling of substrate is opposite. Under the specific processing conditions, the critical condition for continuous epitaxial growth is that the substrate preset temperature $T_{sub} \leq +90\,^{\circ}C$. When the substrate preset temperature T_{sub} is below +90 °C, the height ratio of melting depth to total height of the molten pool is larger than that of stray grain, ensuring that stray grains can be completely remelted and the continuous columnar dendrites during the multi-layer laser powder deposition process on (001) surface of single-crystal substrate can be achieved.

1. Introduction

In recent years, in order to increase the fuel-use efficiency of gas turbine engines, nickel-base single-crystal (SX) superalloys have been widely used as the material of hot-section components such as blades, blisks, and vane seal segments [1]. The main advantage of SX over polycrystalline nickel-base superalloy is their improved high-temperature creep and thermal fatigue resistance, due to the suppression of grain boundary strengthening elements and the elimination of grain boundaries [2]. Under extremely severe working conditions of high-temperature and high-pressure, the service life of these high-cost SX components is limited by the thermal fatigue cracks and tip erosion, leading to a loss of turbine efficiency [3]. The replacement of the these high-value SX components contributes largely to the operation cost of modern gas turbines [4]. Therefore, effective refurbishment and repair techniques which extend the lifetime of SX components are of great economic interest and desirable [5]. A successful repair technique should retain a SX solidification microstructure which is identical to the crystalline structure of the base material in the repaired zone [6].

Laser powder deposition (LPD) process, which allows rapid and accurate addition of controlled amounts of material at the required locations with minimal heat input, has been proven to be a very promising and effective technology in restoring the worn SX components [7]. However, the major challenge in the LPD process of SX superalloy is the stray grain formation which appears as misoriented and equiaxed grains in the deposited microstructure [8]. Stray grains, once form, suppress the epitaxial growth of columnar dendrites and, furthermore, cause the formation of low melting point grain boundaries which act as the easy path for crack initiation and propagation [9]. Thus, the nickel-base SX superalloys are vulnerable to columnar-to-equiaxed transition (CET).

---

* Corresponding author at: College of Innovation and Entrepreneurship, Southern University of Science and Technology, Shenzhen 518055, China.
E-mail address: liucy3@sustc.edu.cn (Z. Liu).

https://doi.org/10.1016/j.jmst.2018.04.016
1005-0302/© 2018 Published by Elsevier Ltd on behalf of The editorial office of Journal of Materials Science & Technology.

Please cite this article in press as: Z. Liu, Z. Wang, J. Mater. Sci. Technol. (2018), https://doi.org/10.1016/j.jmst.2018.04.016

The CET has been studied by theoretical modeling [10–12] and experimental study [13]. During the low-penetration LPD process of SX superalloy on a substrate with similar material, the crystal growth behaviors are determined by the constitutional supercooling (CS) at the solidification interface. Hunt [14] showed that the CS can be described by the G/V ratio, where G is the thermal gradient and V is solidification velocity at the crystal tip. Gäumann et al. [7] developed Hunt's analytical model for the LPD process of CMSX-4 superalloy on a substrate with [001]/<100> crystallographic orientation normal to the depositing surface. A columnar structure can be obtained when the following condition is satisfied

$$\frac{G^n}{V} > K_{\mathrm{CET}} = a\left\{\sqrt[3]{\frac{-4\pi N_0}{3\ln(1-\phi_c)}}\,\frac{1}{n+1}\right\}^n, \tag{1}$$

where G is the temperature gradient, V is the solidification velocity of the columnar dendrite front, K_{CET} is the critical value of CET, a and n are material dependent parameters, N_0 is the nucleation density in the liquid. A parameter ϕ_c is defined as the critical value of areal fraction ahead of the advancing solidification front that is comprised of newly nucleated grains. High thermal gradient G and low growth velocity V tend to benefit the epitaxial growth of columnar dendrites.

For the worn-tip repair process of SX turbine blades, [001]/<100> crystallographic orientation is usually normal to the laser depositing surface. Layers of SX material are deposited on the top surface of blades to regenerate a new tip. In order to achieve continuous SX microstructure in multi-layer tip-repair process, the formation of stray grain must be avoided or completely remelted and resolidified to the base crystal orientation. Increasing the thermal gradient G along the [001]/<100> crystallographic orientation (normal direction of blade tip) of substrate can effectively increase the ratio of $|G_{001}|^n/|V_{001}|$, which can prevent stray grain formation and promote the remelting of stray grain between layers. Meanwhile, the primary dendrite arm spacing (PDAS) also relates to the thermal gradient G and solidification velocity V at the solid-liquid interface [15]. For the rapid solidification processing of LPD of CMSX-4 superalloy, the PDAS follows the proportional relation $w \sim G^{-0.5}V^{-0.25}$ [16], where w is the PDAS. Increasing thermal gradient G can decrease the PDAS. Small PDAS restrains the segregation and benefits the homogenization of chemical elements. During the LPD processing, the thermal gradient G is determined by many factors such as laser power, scanning speed, substrate preset temperature. Decreasing the laser power or increasing the scanning speed can not only effectively increase the thermal gradient, but also decrease the linear laser energy absorbed by molten pool and correspondingly changes deposited bead geometrical size. For the specific applications such as worn-tip refabrication of SX turbine blades, the geometrical size of deposited bead should keep stable. Adjusting the substrate preset temperature can change the thermal gradient with little effect on the linear laser energy of molten pool. Meanwhile, adjusting the substrate temperature has been proven to be an effective method to influence the microtexture and morphology of thin film materials [17,18]. Therefore, for given processing parameters such as laser power, scanning speed and powder feeding rate, controlling the substrate preset temperature is a useful method to optimize the SX-processing window and microstructure. and the effect of substrate preset temperature on CET and PDAS in LPD process of SX superalloy has never be analyzed in detail.

In this study, the effect of substrate preset temperature on the crystal growth and microstructure formation in the deposited bead was analyzed by an improved mathematical model. LPD experiments with specific SX superalloy were conducted to verify the computational results. The results of simulation and experiments were compared and discussed.

2. Mathematical modeling

Fig. 1 shows the schematic of 3D mathematical transient LPD model of SX superalloy improved from the author's previous work [19,20] with modified laser-powder interaction model. The previous model can not only quantificationally calculate the complex transport phenomena such as laser-powder interaction, tempera-

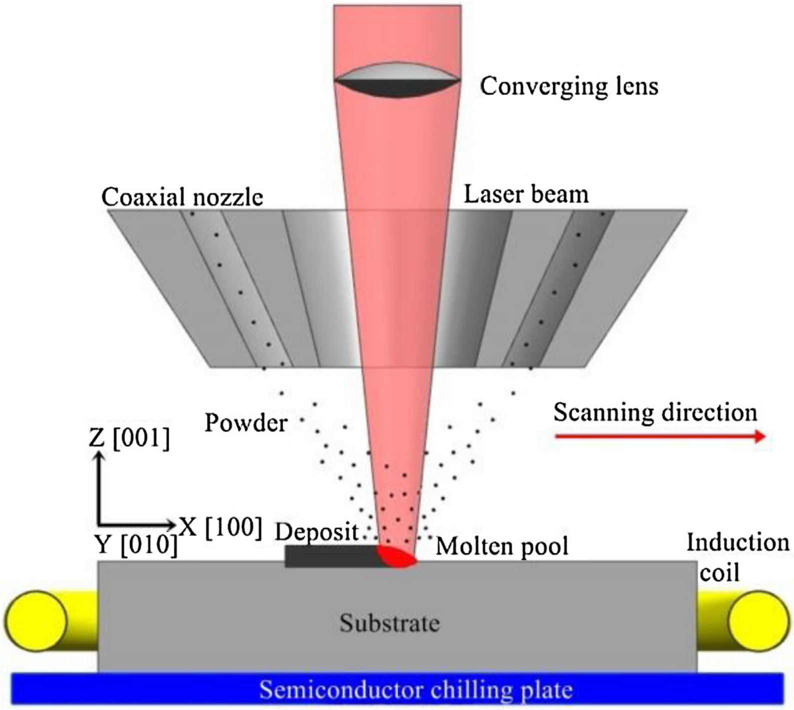

Fig. 1. Schematic of the coaxial LPD process of SX superalloy with controlling of substrate preset temperature.

Please cite this article in press as: Z. Liu, Z. Wang, J. Mater. Sci. Technol. (2018), https://doi.org/10.1016/j.jmst.2018.04.016