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Control of crystal orientation and continuous growth through inclination of coaxial nozzle in laser powder deposition of single-crystal superalloy

Zhaoyang Liu[a,*], Huan Qi[b], Liang Jiang[c]

[a] *School of Material Science and Engineering, Shanghai Jiao Tong University, 200240, China*
[b] *University of Michigan-Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, 200240, China*
[c] *Institute of High Temperature Alloy, Central South University, 410012, China*

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ABSTRACT

The effects of inclining angle of the coaxial nozzle in the longitudinal section of deposited bead on the molten pool geometry and the corresponding crystal growth in laser powder deposition of single-crystal superalloy are studied through the coupling of a numerical FLUENT program and a three-dimensional transient transport phenomena mathematical model. Systematical experiments with single-crystal nickel-based superalloy were conducted to verify the computational results. The results show that the inclination angle of the coaxial nozzle in the longitudinal section of deposited bead has a predominant effect on the molten pool geometry and the solidified microstructure. The inclination of coaxial nozzle reduces the height of the molten pool while increases the melting depth compared to the normal-direction deposition. The epitaxial grain growth in the deposited bead is enhanced when the coaxial nozzle inclines toward the laser scanning direction, while it is restrained as the nozzle inclines toward the opposite direction. When the coaxial nozzle inclines to a +45°, the ratio of melting depth to the height of equiaxied stray grain on the top of the previous layer of deposited bead exceeds 1.0, which implies that the deposited layer can completely remelt the stray grains in the previous layer. The capacity of continuous-epitaxial grain growth can be therefore achieved through the nozzle inclination effectively. This method can be used to optimize and control the processing parameters and broaden the processing window for a single-crystal turbine blade tip repair.

1. Introduction

Single-crystal (SX) superalloy has been used on high-temperature blades and vanes in gas-turbines (Schlachter and Gessinger, 1990). In order to extend the working lifetime of worn-tip SX turbine blades, a successful repair technology should ensure the preservation of the original SX orientation, i.e., the metallurgical microstructure of the repaired material maintains a continuous crystal growth and extends epitaxially in the same crystalline direction from the substrate. In the past decades, laser powder deposition (LPD) technology has become a very promising and effective repair technology in restoring SX alloys (Gäumann et al., 2001). Gäumann et al. (1999) coupled an epitaxial-growth characteristic model of SX superalloy and the LPD technology in a process of epitaxial laser metal forming (E-LMF). They showed that the fine columnar dendrites can grow epitaxially from the SX substrate into deposited bead, which can be used to restore the worn tip of SX blades. However, the major challenge in the LPD process of SX superalloy is the stray grain formation which appears as misoriented and equiaxied grains in the deposited microstructure (David et al., 1997). 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 (Babu et al., 2004). Thus nickel-based SX superalloys are vulnerable to stray grain formation and the resultant degradation of creep resistance and formation of cracks (David et al., 1997).

Many researchers have studied the mechanism of stray grain formation through mathematical models and experimental approaches. The results show that the stray grain formation is due to the equiaxed grain nucleation and growth ahead of the solidification front when the extent of constitutional supercooling (CS) is

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[*] Corresponding author.
E-mail address: zhaoyang_liu@sjtu.edu.cn (Z. Liu).

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large enough (Flemings, 1974). Hunt (1984) 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 solidification boundary. Gäumann et al. (2001) developed Hunt's morphological transition of growing dendrites model, and derived a simplified analysis applicable to complex multi-component alloy systems. It was demonstrated that a fully columnar dendritic structure can be obtained when the ratio G^n/V exceeds a critical value (n is a material-dependent constant). Low temperature of substrate, low laser power and large scanning speed can advance the continuous epitaxial growth of columnar dendrite in a multi-layer LPD process. Similarly, Rappaz et al. (1989, 1990) and Liu and DuPont (2004, 2005) used minimum growth velocity criterion to describe the crystal growth pattern. Their work contributes to the understanding of the effects of the molten pool shape and substrate crystallographic orientation on the microstructure formation in a laser weld pool. Recently, Anderson et al. (2010) combined a heat transfer and fluid flow model and the Gaumann's columnar-to-equiaxed transition (CET) model to analyze the effect of processing parameters on stray grain formation. Their work provides a method to study the molten pool size and associated crystal growth through a transient mathematical model. A three-dimensional (3D) transient mathematical model was developed previously by the authors (Liu and Qi, 2015a, b) to predict the crystal growth and microstructure formation during transient LPD process of SX superalloy. The results show that processing parameters and substrate crystalline orientation affect the molten pool shape, sizes and the associated CET solidification condition at the solidification boundary, which determines the microstructure formation in the deposited bead.

The repair of a worn squealer tip of the SX turbine blade often requires a multi-layer LPD process. In order to achieve continuous SX microstructure in multi-layer LPD process, any formed stray grains must be avoided or completely remelted and resolidified to the base crystal orientation. Small layer height and high scanning speed of laser beam were used to ensure the complete remelting of stray grains (Do et al., 2013). Methods to reduce the fraction of stray grains and increase the melting depth in a deposited bead can extend the epitaxial grain growth processing window as well as to increase the efficiency of a multi-layer LPD repair process. During LPD process, the molten pool size and shape is determined by many factors such as laser power density, energy absorption, powder capture efficiency and the material fluid flow behavior (Liu and Qi, 2014). Previous study has shown that the inclination of the substrate crystal orientation can effectively influence the epitaxial growth height of SX deposit layer in a coaxial LPD process (Liu and Qi, 2015a,b). The angle between the incident laser beam and substrate crystal orientation can be also and more easily adjusted by the inclination of the coaxial nozzle. However, inclining coaxial nozzle may affect the powder flow concentration distribution by gravity effect. Meanwhile, the inclination of coaxial nozzle varies the laser energy absorption ratio between the powder flow and the base material, which influences the melt pool geometry, the inside fluid flow, and finally the distribution of temperature gradient at the solidification boundary. Therefore the inclination of coaxial nozzle in a LPD process can be effectively used to vary the molten pool geometry and enhance the epitaxial growth capability for multiple-layer SX alloy deposition.

In this study, a numerical FLUENT program was used to predict the concentration distribution of coaxial powder flow. The results of FLUENT program were coupled into a 3D transient mathematical model to simulate the crystal growth and microstructure formation in LPD process of SX superalloy. LPD experiments with SX superalloy were conducted to verify the computational results of microstructure in deposited bead. The effects of inclination angle of coaxial nozzle on crystal growth and microstructure formation during LPD process of SX superalloys were systematically studied through mathematical model and experiments.

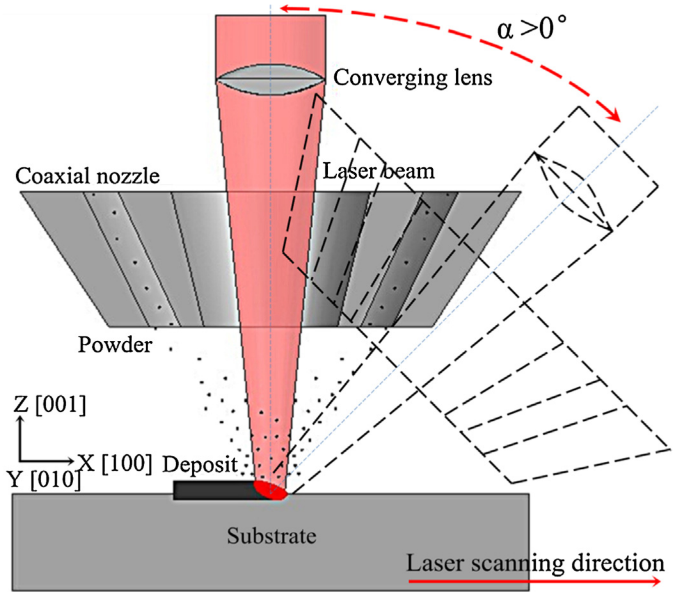

Fig. 1. A schematic of the coaxial LPD process with inclination angle α of nozzle in longitudinal section of deposited bead.

2. Mathematical model

A schematic of the coaxial LPD process is shown in Fig. 1. In this process, the powders are fed into the laser spot region through an annular cone-shaped channel coaxially with the laser beam. In the powder stream, the particles travel through the laser irradiation zone in which they are rapidly heated up. Some powder particles near the center of laser beam are melted. While some powder particles near the outer boundary of laser beam are not or partly melted. These powder particles, once captured by molten pool, absorb energy from liquid metal and are melted immediately. The angle α was used to simplify the description of the inclination angle of coaxial nozzle in the longitudinal section of deposited bead. The $\alpha = 0^\circ$ represents the coaxial nozzle is in the normal direction of substrate surface. When the coaxial nozzle inclines to the laser scanning direction (pull angle), α is positive. When coaxial nozzle inclines to the opposite direction (push angle), α is negative. The symmetricity of the coaxial powder flow is affected by the gravity which will make the focus of the powder flow deviate from the laser beam as the coaxial nozzle inclines with an angle α. As a result, the laser-powder interaction and the powder capture efficiency in the molten pool is changed from the normal condition. To accurately predict the molten pool size and the resultant crystal growth during solidification, a two-phase fluid flow model is firstly developed to study the powder flow distribution under the coaxial nozzle with various inclination angles. Then these results are used as the input in a 3D self-consistent LPD model which was previously developed in (Liu and Qi, 2015a) to predict the molten pool and the associated crystal growth behavior.

2.1. Numerical modeling of gas and powder flow

A discrete model is built using FLUENT software package to evaluate the coaxial powder stream behavior with the inclination of coaxial nozzle. Fig. 2 shows the dimensions of the discrete model. The cone-shaped channel through which the powder is delivered has an angle of 21° relative to the center axis. The diameters of the inner and outer nozzle orifice measured from real configuration