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Modeling of thermal behavior and mass transport in multi-layer laser additive manufacturing of Ni-based alloy on cast iron

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ABSTRACT

During multi-layer additive manufacturing, multiple thermal cycles and addition of dissimilar-metal powder, even functionally graded materials (FGMs), lead to complicated transport phenomena and solidification behavior in the molten pool, which significantly impact the microstructure evolution and mechanical properties of deposited part. In this study, a predictive three-dimensional numerical model is developed to understand the multi-physical processes such as thermal behavior, Marangoni effect, composition transport, solidification behavior, and dendrite growth in multi-layer additive manufacturing of Ni-based alloy on cast iron. Dimensional analysis is performed to simplify the force balance equation on the liquid-gas interface, which determines the dynamic profile of molten pool. The conservation equations of mass, momentum, enthalpy and concentration are solved in parallel. Transient temperature distribution and thermal cycles at different locations are obtained. The solidification parameters at the liquid-solid interface are evaluated to interpret the solidification microstructure. The distribution of alloy elements and composition profile (Ni and Cr) are also present and compared with the relevant experimental results. The results show that the cooling rate declines progressively as the subsequent layers deposit, which results in the coarser solidified grains in the upper of part. Even though the powder and substrate can be efficiently mixed to be a homogeneous molten pool, a non-uniform concentration distribution is observed at the bottom of the deposited part, which agrees well with the experimental composition profile using Energy Dispersive Spectrometer (EDS).

1. Introduction

Laser powder blown additive manufacturing is an advanced manufacturing process for near-net-shape materials, even functionally graded materials (FGMs), in aviation, aerospace, automobile, and other industries [1,2]. During this process, multi-physical and multi-scale phenomena simultaneously occur and impact the microstructure and mechanical properties of parts. The metallic powder flow interacts with the focused laser beam before depositing on the base metal. A molten pool is rapidly formed on the surface of the substrate. The addition of powder and solidification of molten pool result in the formation of macro-structure along the laser scanning path. Temperature gradient on the surface of molten pool leads to a significant spatial gradient of surface tension, which drives a strong convection of liquid metal (Marangoni flow) and facilitates convective heat and mass transport in the molten pool [3,4]. Multiple thermal cycles due to the bidirectional laser scanning and composition redistribution owing to the addition of dissimilar-metal powder affect the microstructure evolution and mechanical properties of deposited layers [5,6]. In order to design the suitable process parameters and regulate the microstructure evolution, composition distribution and mechanical properties of the manufactured part, a thorough understanding of the details of transport phenomena, Marangoni effect, and solidification behavior is crucial [7]. What is required but currently unavailable is a predictive, well-tested, multi-physical process model. It can be utilized as a foundation for understanding the basic physical phenomena and selecting the key process parameters, and forming parts with sound microstructure, non-defect, and excellent performances based on scientific principles.

Because of difficulty in modeling and high computational costs, most current models concentrated on the single-track additive manufacturing process. A transient 3D numerical model was built to obtain the thermal distribution and velocity field within the

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molten pool during additive manufacturing process [8]. In order to simulate the powder addition process, a computationally intensive approach, Level-Set method, was introduced into the numerical model to capture the liquid-gas interface of molten pool [9]. Sets of dimensionless conservation equations were established and solved to examine the molten pool dimensions, temperature distribution and cooling rate in direct laser deposition [10]. Gan et al. proposed a heat transfer and multicomponent mass transfer model to predict the thermal behavior and composition profile in laser additive manufacturing. Some key solidification parameters such as temperature gradient, growth rate and cooling rate were also evaluated based on the temperature field [11].

With the development of Laser Engineered Net Shaping (LENS) and three-dimensional laser repairing, it is very urgent to understand the transport phenomena and solidification behavior in the multi-layer and multi-track process [12,13]. A mathematical model in multi-track laser hardening of AISI 4140 steel was proposed to investigate multiple hardening and overlapping passes [14]. A 3D heat transfer finite element model was used to obtain the molten pool geometry, thermal cycles and hardness distributions in laser additive manufacturing [15]. Numerical simulation of heat transfer and its influence on the scale and morphology of microstructure in electron beam additive manufacturing of IN718 was reported. The columnar to equiaxed transition was examined by using an improved grain growth model [16]. However, in above studies, liquid metal flow within the molten pool was neglected, which has been proven to be the dominative mechanism of heat and mass transfer in the molten pool [11,17].

Few researchers considered the liquid metal flow (Marangoni effect) within the molten pool during the multi-track or multi-layer additive manufacturing process [18–20]. A two-dimensional (2D) transport phenomena model in multi-layer additive manufacturing was reported. An arbitrary Lagrangian-Eulerian Method (ALE) was implemented to track the liquid-gas interface of molten pool [18]. A predictive heat transfer and fluid flow model was proposed during the double-track additive manufacturing process. Heat transport, fluid flow, and dynamic surface evolution were included in the simulation [19]. Debroy et al. developed a transient, 3d, transport phenomena numerical model for the multi-layer direct laser deposition with coaxial powder feeding [20]. The evolution of experimental solidification texture was also evaluated in comparison with the numerical simulation [5]. Although the additive manufacturing of dissimilar-metal powder (i.e. compositions of the powder are different from that of the substrate) and the FGMs have been used in the fields [21–23], the solidification behavior, mass transfer, element redistribution, and solute segregation have not been thoroughly understood in multi-layer or multi-track additive manufacturing.

In this paper, in order to understand the heat transport, solidification behavior and solute transport in multi-layer additive manufacturing, a 3D, transient, heat and mass transfer, and liquid metal flow numerical model is developed for the laser additive manufacturing of Ni-based alloy on cast iron. The conservation equations of mass, momentum, energy and concentration are solved using a boundary-fitted curvilinear coordinate system to consider the transient changes in the geometry. Temperature distribution and thermal cycles at different locations can be predicted. Based on the computed temperature distribution, the solidification parameters at the liquid-solid interface are evaluated to interpret the evolutional microstructure. Furthermore, the redistribution of alloy elements and composition distribution during the process is present. The computed molten pool geometry and composition profile are compared with the relevant experimental results.

2. Numerical modeling

The multi-physical phenomena in the multi-layer additive manufacturing are shown in Fig. 1. The assumptions used in this study are listed [20,24]:

1. The liquid metal flow within the molten pool is laminar, incompressible, and Newtonian.
2. The surface tension is temperature-dependent and composition-independent.

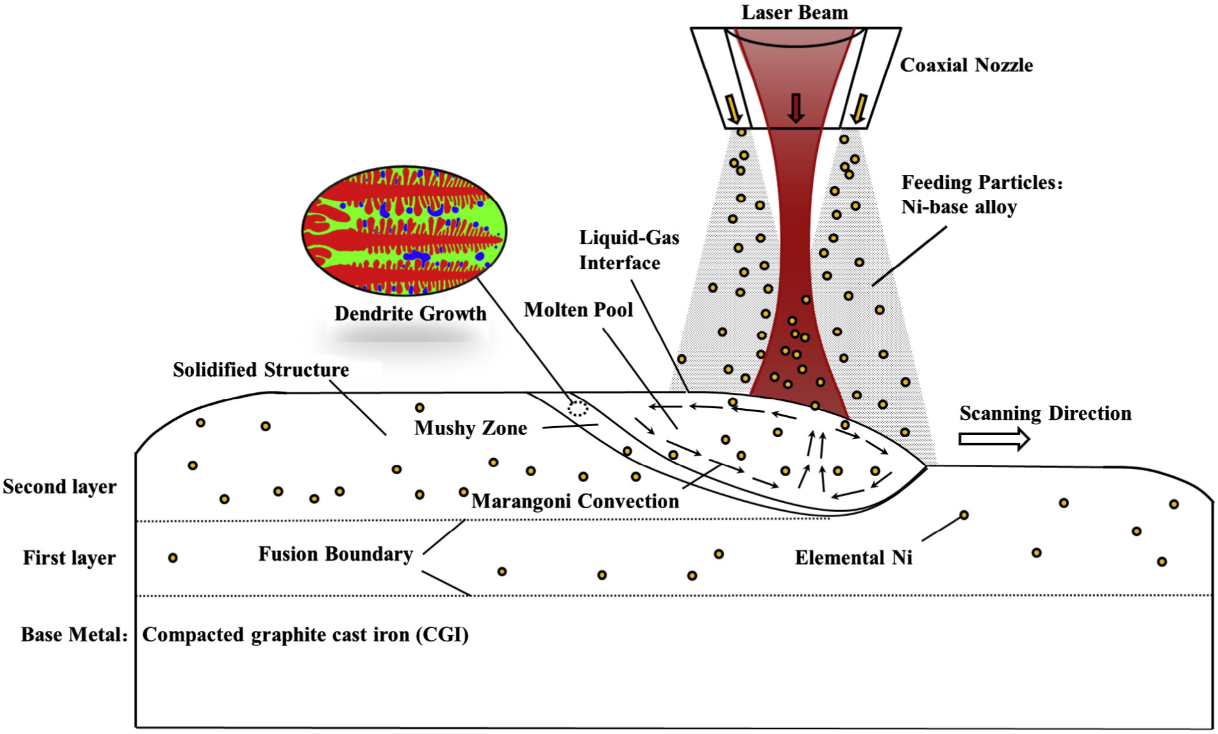

Fig. 1. Multi-physical phenomena in multi-layer additive manufacturing.