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Numerical and experimental study of laser aided additive manufacturing for melt-pool profile and grain orientation analysis

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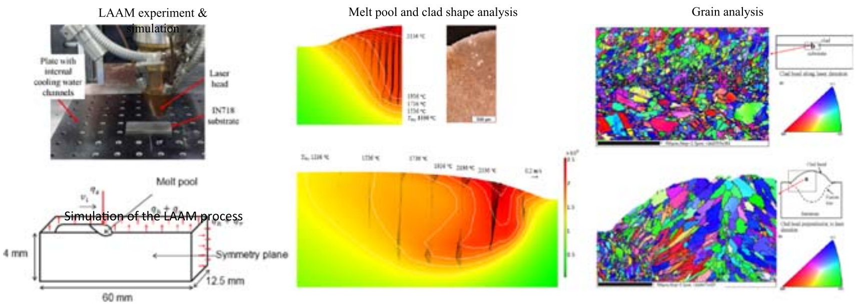
HIGHLIGHTS

- The process of laser aided additive manufacturing was simulated with moving mesh to represent the clad bead shape.
- Heat input equation considering both flight particle heating and particle phase change was developed.
- Numerical results had errors less than 10% for the 7 sets of experiment with different process parameters.
- The grain size and orientation were investigated through combination of temperature gradient and solidification rate.

GRAPHICAL ABSTRACT



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ABSTRACT

Laser aided additive manufacturing (LAAM), a blown powder additive manufacturing process, can be widely adopted for surface modification, repair and 3D printing. A robust numerical model was developed to simulate convective fluid flow and balancing of surface tension forces at the air-fluid interface to predict melt-pool free surface curvature and solidified clad dimensions. The free surface physical interface was calculated using the Arbitrary Lagrangian Eulerian (ALE) moving mesh approach. Powder deposition efficiency was considered by activating mesh normal velocity at melted regions based on localized powder mass flux intensity from the discrete coaxial powder nozzles. The heat flux equation used for representing the laser heat source considered attenuation effect from the interaction between the powder jets and laser as well as heat sink effects of un-melted powder particles entering the melt-pool. The predicted thermal gradient directions agree well with grain growth orientations obtained from electron backscatter diffraction (ESBD) analysis in three different cross-sectional orientations. Experimental validation of clad width, height and melt-pool depth shows a maximum error of 10% for a wide range of processing parameters which consider the effects of varying laser power, laser scanning speed and powder feeding rate.

1. Introduction

Laser Aided Additive Manufacturing (LAAM), Laser Metal Deposition (LMD) and Laser Engineered Net Shaping (LENS) technologies build incremental additive layers by the simultaneous surface melting and material addition, usually in the form of metal powders or wire [1]. The main advantages of using these technologies are the higher deposition rates and no supporting structures required, compared with powder-bed based additive manufacturing (AM) methods such as selective laser melting (SLM). However, the blown powder processes are more complex, which incorporate gas-powder [2], liquid-solid

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interactions and transformations during the whole process. As a result, process optimization based on the experiments is relatively complicated, especially when microstructure and mechanical properties need to be considered. Hence, effective numerical simulation of the process is necessary to predict the geometry & dimension of the clad bead, temperature gradient, heat and mass flow, and resultant microstructure and mechanical properties of the deposited material. This will provide the guidance to the efficient process development.

More recent numerical models utilize thermal gradients and temperature evolution results to further predict metallurgical field. These include solidification grain size predictions for aluminum alloy [3,4] and dendritic features (size, orientation and spacing) of Inconel 718 built by powder-bed AM technology [5]. Multi-scale finite element model developed by Nie et al. [6] demonstrated how the ratio of temperature gradient to solidification rate can influence solidified Laves phase morphology in IN 718 superalloy. The formation of coarse continuous Laves phase in IN 718 is detrimental to ductility, tensile strength and fatigue performances. The control of IN 718 grain texture was also investigated by Raghavan et al. [7]. The simulated thermal field for multi-layered laser cladding process was also employed to correlate with the microstructure of Ti-6Al-4V [8]. Therefore, mechanical properties of parts built by AM can potentially be tailored by controlling the solidification conditions based on predictions and insights obtained from numerical modeling. In addition, surface quality of clad was also observed to be influenced by melt-pool fluid flow and disturbances [9].

Various numerical models simulating only the thermal and melt-pool fluid fields were also reported with in-depth investigation about the effects of process parameters on melt-pool dynamics and clad geometries. Kumar and Roy [10] simulated the laser cladding process with the inclusion of heat conduction, phase change, fluid flow etc. They also conducted parametric studies on scanning speed and thermocapillary gradient to analyze their influence on melt-pool flow field and clad built-up geometry, but lacked experimental results. Qi et al. [11] conducted numerical study on the LENS process based on coupling of fluid velocity with temperature. They found that melt-pool length and width increase with increasing laser power, while clad height increases almost linearly with laser power. They also reported a maximum error of approximately 22% when comparing with experimental melt-pool sizes. Morville et al. [12] used a 2D finite element model to identify the process parameters resulting in high dilution ratio, which according to their study, leads to better surface finishing. Lee and Farson [13] analyzed the influence of thermocapillary gradient on the build geometry, with detailed study on the mechanisms responsible for sidewall non-uniformity and deposit bulge. However, details on experimental validations of the deposits geometries and melt-pool depth were not reported. Manvatkar and DebRoy [14] presented a thermal and fluid model for predicting the geometry of multi-layered deposited austenitic stainless steel. The simulated melt-pool dimensions agreed well with experimental results for a set of specified process parameters, but melt-pool curvature is not considered.

In LAAM process, both the laser heat application and powder mass addition act upon the curved surface of the melt-pool front. The surface tension forces are coupled with melt-pool curvature and fluid flow field to give the solidified clad bead geometry. Therefore, it is important for the numerical model to compute melt-pool curvature accurately [15]. The Arbitrary Lagrangian Eulerian (ALE) moving mesh method is utilized in this work for more accurate modeling of the melt-pool free surface and mass conservation as compared to alternatives methods such as volume of fluid (VOF) and level set (LS) [16]. The ALE method computes the physical element node displacement which allows the normal flux vectors of the incident thermal and mass fluxes to be applied directly on the physical (fluid/air) boundary [17]. The ALE method is also more accurate in computing the local surface curvature [18], which is significant for applying the novel overall heat flux equation proposed in this work. The computed free surface boundary local curvature is also considered in the powder mass flux addition, as well as definition of mesh velocity to account for melt-pool powder catchment for clad deposition.

From the review above, substantial work has been reported for numerical modeling of the various deposition processes. However, due to the complexities of the processes, no numerical model considers the whole deposition process to include powder feeding, laser-powder interaction, temperature field, melt-pool dynamics and solidification. It also lacks the verification of the numerical model through detailed experimental study. Hence, no model yet can be considered absolutely predictive in terms of melt-pool and clad geometries, as well as microstructure evolution. Hence, the main objective of this work is to develop a more robust numerical model which extends the predictive capability under a wider range of process parameters with inclusion of experimental studies.

In this paper, a numerical model for laser aided additive manufacturing of Inconel 718 is presented and is validated by 7 experimental tests using various process parameters with numerical results errors within 10%. The powder injection delivery method is a unique characteristic of the LAAM process. A semi-empirical model has been developed in this work to capture the effects of powder dynamics on the laser power attenuation, in flight particle heating and particle phase change (latent heat of fusion) upon entering the melt-pool. Experiments were performed to measure the particle velocity, powder focus diameter, substrate laser absorptivity and used as input parameters in the mathematical model. From the obtained numerical results, in-depth analysis of the melt-pool profile, flow velocity, temperature distribution, and cooling rate will be performed. The cooling rate ($-\frac{dT}{dt}$) as a combined effect of temperature gradient (G) and solidification rate (R) is analyzed in the discussion. The relationship between solidification rate and profile of melt pool are also discussed. This approach allows us to investigate the change of cooling rate near the melt pool in more detail and to get a better understanding of the grain size distribution during the melt pool solidification.

2. Experiments

2.1. Powder jet

The powders were delivered using a discrete coaxial nozzle with three powder jet channels. The powder jets from the discrete powder nozzle are illustrated in Fig. 1(a). The laser power attenuation model

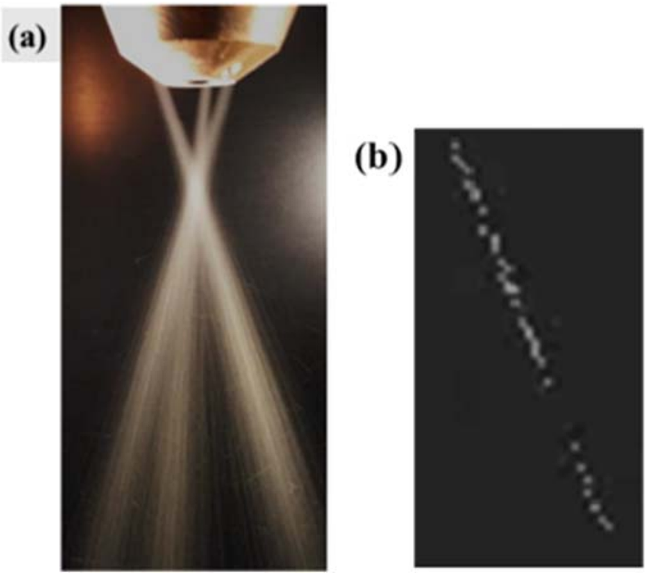

Fig. 1. a) Discrete powder jets coming from the nozzle exit located at the base of the laser head. b) Single cluster of powder particles monitored to estimate particle velocity.