Optics and Laser Technology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Optics and Laser Technology

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

A new physics-based model for laser directed energy deposition (powder-fed additive manufacturing): From single-track to multi-track and multi-layer

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HIGHLIGHTS

- A novel high fidelity analytical model for multi-layer/track deposition is developed.
- Thermal field prediction with residual heat in multi-layer/track deposition is done.
- Track geometry modeling with considering the melt pool bead spreading is studied.
- The most sensitive parameter in the clad height modeling is powder feed rate.

ARTICLE INFO

Keywords:
Additive manufacturing
Laser direct energy deposition
Clad geometry

ABSTRACT

A physics-based process model of laser powder-fed additive manufacturing (LPF-AM), a class of directed energy deposition, is established in this paper. The model can perform an efficient prediction of the melt pool dimension, wetting angle, dilution, process heating/cooling rates and clad 3D profiles from single-track to multi-track and multi-layer deposition, and has the potential to be employed for the fast process optimization and controller design. The novelty of the model lies in three fronts: (1) the melt pool geometry variation as the liquid melt pool bead spreading on the solid surface is counted by the wetting angle alternation, in which the dynamic wetting angle is computed based on the Hoffman-Voinov-Tanner law; (2) the heat accumulation effect in the multi-track, multi-layer scanning is compensated by adding the accumulated temperature field to the initial temperature field of the following layers/tracks. The accumulated temperature is calculated by summing up the transient temperature solutions of the prior layers/tracks based on the superposition principle; and (3) the feeding powder distribution is incorporated into the transient thermal field simulation of the multi-layer and multi-track deposition process by analytically coupling the powder mass flows and laser heat flux, in which the powder mass flow is expressed as an equivalent heat flux. Experiments were conducted to validate the built model. The single-track measurements (clad height, clad width, dilution and wetting angle) show that the prediction error of the built model is less than 14%. The multi-track and multi-layer measurements also indicate that the model can perform a high accuracy dimension prediction of the built features. Besides, a sensitivity analysis was conducted based on the built model and the results show that the powder feed rate is the most sensitive parameter that substantially varies the clad height, followed by the process speed, whereas the specific heat has the least sensitivity.

1. Introduction

In laser powder-fed additive manufacturing (LPF-AM), a class of directed energy deposition, the metal powder is carried by the inert gas to the laser beam focusing area and melted instantly with forming a liquid melt pool bead, which then wets the solid prior layers or substrate to form a metallurgical bond and eventually creates 3D parts in a layer by layer way. As laser additive manufacturing has a high cooling rate [1] and a low solid-liquid interfacial free energy as well as a small nucleus critical radius for promoting heterogeneous nucleation [2], the LPF-AM fabricated parts will typically exhibit finer grain size than that processed by the traditional manufacturing process (e.g., casting), resulting in higher mechanical properties. Nevertheless, a large variety of operating parameters can affect the powder concentration, heat conduction, layer-to-layer adhesion and finally determine the clad quality and geometric accuracy [3]. Defects (e.g., cracks, porosity, and un-

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https://doi.org/10.1016/j.optlastec.2018.08.015
Received 4 June 2018; Received in revised form 7 August 2018; Accepted 9 August 2018

Please cite this article as: Huang, Y., Optics and Laser Technology (2018), https://doi.org/10.1016/j.optlastec.2018.08.015

melted powder) may be induced by improper parameter settings. By contrast, full-density and high-performance parts can be fabricated based on the optimized process parameter [4]. But the experimental optimization of the process is time-consuming and costly due to the large number of operating parameters. In addition, the LPF-AM process has a high sensitivity to disturbances [5]. A small change of process parameters (e.g., laser absorptivity, initial temperature, process speed) may induce significant variations in the transient heating/cooling rate, dilution (percentage of surface layer composed by melting the substrate) and the overall melt pool shape, which may affect the deposited clad layer and eventually influences the fabricated part’s mechanical integrity, properties and the process stability. To date, the low level reliability and repeatability of LPF-AM fabrication are still the major barriers for its industrial application [6,7].

A physics-based model for the LPF-AM process can help to build the relationships between the process parameters and the clad geometry and quality, and it is essential for controller design in the process control to improve the process reliability and stability. Furthermore, control-oriented models should be fast and accurate enough to stabilize the controller. Therefore, numerical models based on finite element method may be difficult to be applied for process control due to their high computational cost. Time-efficient empirical-statistical models developed with experimental data have been extensively used for process optimization and control. Fathi et al. [8] developed a sliding mode controller for closed-loop control based on a parametric Hammerstein model. Lijun [9] built a generalized predictive controller based on a state space model for predictive control of the melt pool temperature. Jin et al. [10] achieved offline shape deformation control by extending the established Bayesian models from Qiang et al. [11]. Despite these excellent successes, the accuracy of the empirical-statistical models will be directly affected by the corresponding evaluation approaches or experimental conditions, and the models may provide broadly similar but not exactly equal results [12]. In addition, only limited numbers of process variables are taken into consideration in these models, but research from Qi and Mazumder [13] shows that the fabricated part characteristics may be strongly affected by around 12 factors.

Alternatively, a physics-based analytical model may be able to provide a great platform for the process optimization as well as process control. Kaplan and Groboth [14] developed an analytical process model to estimate the substrate temperature and the clad geometry based on the process mass and energy balances. They point out that the process powder catchment and laser energy distribution are influenced by the powder flux distribution. Yuze et al. [15] built a comprehensive analytical model for the single-track dimension and catchment efficiency prediction, in which the attenuated laser power intensity and the heated powder spatial distribution are taken into consideration. Doumanidis and Kwak [16] established an analytical model for clad geometry and melt pool temperature estimation by sequentially solving the mass and energy balance and the thermal conduction in the substrate. And the built model is successfully incorporated into the on-line closed-loop control. Tan et al. [17] established an analytical model to estimate the clad layer geometry based on the on-line temperature measurements. They indicate that the model can be potentially used for on-line feedback control. Qian et al. [18] developed a multivariable analytical model to predict the steady state melt pool temperature and the single-track dimension. And based on the developed model, a feedback linearization control for the melt pool height and temperature was achieved.

However, most of the above models are limited for single-track modeling and ignored the heat accumulation effect during the multi-track and multi-layer scanning. The accumulated heat from the prior layers/tracks may not be completely dissipated by heat conduction before the next layer/track applied due to the high scanning rate. Therefore, the following layers/tracks may form on a locally preheated zone with a higher initial temperature compared with that of the prior layers/tracks, which may induce non-uniform melt pool geometries and different wetting conditions. Sammons et al. [19] built a multi-layer model by adding a solidification rate into the mass balance equation for counting the heat transfer effect of the prior layers to the current layer. Jianyi et al. [20] extended the above single-track model built by Qian et al. [18] to a multi-layer model by considering the residual heat from the prior layers. They built a varying initial temperature model for the following layers with a dummy moving heat point source that is solved by the quasi-steady-state Rosenthal's solution.

Inspired by the above references, a new physics-based model for LPF-AM that can be extended from single-track to multi-track and multi-layer deposition was built in this paper. For the multi-track and multi-layer scanning, the accumulated temperature field is added to the initial temperature field of the following layers/tracks to quantitatively describe the accumulated heat effect. Thus, a dynamic thermal field of the multi-track and multi-layer deposition can be built and the corresponding heating/cooling rate and geometry profile can be estimated. The other contribution of this model is that the powder mass distribution is incorporated into the transient thermal field simulation of the multi-layer and multi-track deposition process by expressing the powder mass flow as an equivalent heat flux. Besides, another important difference of our model from the existing work lies in the consideration of the melt pool shape variation as the liquid melt pool bead spreading on the solid surface, in which an isothermal wetting case is assumed and a dynamic contact angle is solved based on the Hoffman-Voinov-Tanner law [21]. Although the realistic molten metal droplet wetting is a non-isothermal configuration [22], the isothermal wetting assumption here may not spoil the validity of the proposed model since the temperature variation may be negligible during the tiny time of liquid bead spreading. Experiments were conducted with a LPF-AM setup developed in-house through iron-powder deposition, in which the built model was validated by using the measurements of different builds, including single-track, multi-layer thin-wall structure and multi-track/multi-layer patch structure. Sensitivity analysis was done to investigate the effects of the material properties and process parameters on the clad heights of both the single-track and multi-layer thin-wall builds.

2. Model formulation

2.1. Thermal field

In the single-track deposition of the LPF-AM process, each point along the laser scanning path will experience a thermal cycle, in which the transient temperature may range from the ambient temperature to a high temperature (e.g., melting temperature) and then cooling down. To quantify this thermal cycle mathematically, the temperature distribution in time and space domain should be solved. The solution for the temperature rise of an instantaneous point heat source Q in the semi-infinite homogeneous solid with temperature independent properties is given by [23],

$$dT(X,\Delta t)=\frac{Q}{4\rho_P c_P(\pi\alpha_P\Delta t)^{3/2}}\exp\left(-\frac{R^2}{4\alpha_P\Delta t}\right),\quad R=\sqrt{(x-x_c)^2+(y-y_c)^2+(z-z_c)^2} \tag{1}$$

where ρ_P the density, c_P the specific heat, α_P thermal diffusivity, Δt the time elapsed after the instantaneous heating and R is the distance from the interest point $X=(x,y,z)$ to the heat source point (x_c, y_c, z_c). The above solution is derived from Green's function with the absence of convective and radiative heat losses, which has been validated in the context of additive manufacturing process modeling, showing a good agreement with the experiment [24–27]. Research studies [28,29] showed that the heat lost amount by radiation and convection is negligible in comparison to that of the heat conduction. Thus, the heat radiation and convection effects are not considered in this paper.

Based on Eq. (1), for a moving heat source (moving speed v_x, v_y)