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A comprehensive analytical model for laser powder-fed additive manufacturing

Yuze Huang, Mir Behrad Khamesee, Ehsan Toyserkani (PhD PEng)*

University of Waterloo, Department of Mechanical and Mechatronics Engineering, Waterloo, Ontario N2L 3G1, Canada

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ABSTRACT

This paper addresses a comprehensive analytical model for the laser powder-fed additive manufacturing (LPF-AM) process, also known as directed energy deposition AM. The model analytically couples the moving laser beam with Gaussian energy distribution, the powder stream and the semi-infinite substrate together, while considering the attenuated laser power intensity distribution, the heated powder spatial distribution and the melt pool 3D shape with its boundary variation. The particles concentration on transverse plane is modeled with Gaussian distribution based on optical measurement. The model can effectively be used for process development/optimization and controller design, while predicting adequate clad geometry as well as the catchment efficiency rapidly. Experimental validation through the deposition of Inconel 625 proves the model can accurately predict the clad geometry and catchment efficiency in the range of specific energy that is corresponding to high clad quality (maximum percentage difference is 6.2% for clad width, 7.8% for clad height and 6.8% for catchment efficiency).

1. Introduction

The laser powder-fed additive manufacturing (LPF-AM) process is one of the seven classes of AM that falls under the "Directed Energy Deposition" class. The functionality of LPF-AM has attracted multiple industries to embrace its features for coating, repair and part production from single or multiple materials. In the LPF-AM process, the powder stream interacts with the laser beam and attenuates the beam intensity, while the heated powder particles impinge into the melt pool adding mass and energy to the melt pool to form effective deposition. All these interactions affect the melt pool temperature distribution and the final shape of the clad layer.

A comprehensive model is essential to provide the process fluctuation prediction required for the design of comprehensive controllers for real-time closed-loop control of the process [1]. For the development of any closed-loop control algorithm for LPF-AM, the addition of a model-based benchmark is required. However, the model must be fast, simple but accurate enough to stabilize the controller. Therefore, finite elements models are not suitable for this purpose [2]. Analytical model that can effectively be incorporated in high speed hardware may provide a great platform for the real-time control of LPF-AM.

Numerical methods based on finite element methods have also proved popular and can accurately simulate the powder flux distribution [3], laser particle interaction process [4], melt pool formation [5], clad layer geometry [6,7], temperature, velocity and thermal stress fields distribution over the process [8,9]. But such numerical models are increasing the complexity of process modeling and computational time.

Analytical modeling is a classic way for understanding the unfamiliar aspects of the process [10] and acts as a benchmark reference generator inside the structure of closed-loop control system. Picasso et al. [11] established a simple but realistic analytical model for LPF-AM. The powder attenuation effect for the laser beam was accounted with simple geometry intersecting ratio. The heated powder energy was added together with the laser beam energy as the heat source to calculate the substrate temperature field. With the relative simplicity, their model can produce immediate results about scanning speed, powder feed rate and catchment efficiency. Fathi et al. [12] developed a mathematical model of LPF-AM to predict the melt pool depth, dilution and the temperature field with given values of clad height and clad width. They built the mathematical top surface of the melt pool with parabolic equation and solved the heat conduction in substrate to predict the temperature field based on an infinite moving point heat source. Tan et al. [13] built an analytical model to estimate the clad layer geome-

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* Corresponding author at: Department of Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada.
E-mail address: ehsan.toyserkani@uwaterloo.ca (E. Toyserkani).

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Nomenclature

A_{S_2}, A_{S_3}	Melt pool effective projection area, mm^2
C	Specific heat capacity, J/(kg K)
D	Laser spot diameter, mm
E	Specific energy, J/mm^2
$\dot{g}$	Argon gas feed rate, dL/min
h	Clad height, mm
H	Nozzle height, mm
$I(x,y,z)$	Laser beam intensity at point (x, y, z), W
$I_A(x,y,z)$	Attenuated laser beam intensity at point (x, y, z), W
$I_{\mathrm{p}}(x,y,z)$	Heated powder energy intensity, W
$I_{net}(x,y,z)$	Resultant energy source intensity
k	Thermal conductivity, W/(m K)
K	Constant for powder stream boundary line
L	Melt pool length, mm
l_1,l_2	Major semi-axis of the projection ellipse
L_f	Latent heat fusion, J/Kg
$\mathrm{m_p}$	Particle mass, g
$\dot{\mathrm{m}}$	Powder feed rate, g/min
$n(x',y',z')$	Powder number concentration
P_L	Laser power, W
Q_{ext}	Extinct coefficient
r_0	Nozzle internal radius, mm
r_p	Particle radius, µm
$r(z')$, $r(z)$	Powder stream effective radius at z', z mm
R_{0L}	Laser beam waist radius, mm
$R_L(\mathrm{z})$	Laser beam effective radius at z, mm
S_1, S_2, S_3	Melt pool approximation inclined surface
t_n	Nozzle tube thickness (mm)
T_0	Ambient temperature, K
T_m	Material melting temperature, K
T_P (x, y, z)	Particle temperature at point (x, y, z), K
v	Process speed, m/s
v_p	Particle velocity, m/s
w	Minor semi-axis of the projection ellipse, mm
W	Melt pool width, mm
z_0	Laser beam waist position, mm
ΔT	Temperature increment, K
ϕ	Melt pool inclination angle, *degree*
α	Thermal diffusivity, m^2/s
α_w	Brewster effect coefficient
β	Powder laser absorptivity
β_w	Substrate laser power absorptivity
η	Catchment efficiency
θ	Powder stream divergence angle, *degree*
θ_L	Laser beam far-field divergence angle, *rad*
λ_L	Fiber laser wavelength, µm
μ	Thermal conductivity correction factor
$\rho(x',y',z')$	Powder spatial mass concentration, g/mm^3
ρ_p	Particle density, Kg/m^3
σ	Extinction cross section of a sphere particle, mm^2
φ	Nozzle angle, *degree*
Ω	Melt pool boundary

try based on a moving disc heat source model. The melt pool was fitted as an ellipse and the powder catchment efficiency was calculated directly as melt pool and the powder stream area ratio. They also considered the powder flux distribution in clad height prediction and pointed out that both the melt pool length and clad width increasing with decreasing scanning velocity and increasing laser power. Shengfeng et al. [14] proposed a similar analytical model to predict the cladding height and catchment efficiency with assuming the melt pool to be a flat plane on substrate. Experimental results show that the catchment efficiency has the same varying trend with the nozzle angle. Xinyong et al. [15] developed a mathematical model to estimate the catchment efficiency based on mass conservation and kinematic equations, but no consideration was paid to the interaction effect between the laser beam and the particles.

Most of the above analytical models have decoupled the mass and energy flows, ignored the changes of the laser power absorptivity due to the varying of clad geometry(Brewster effect), and calculated the melt pool limits only based upon laser power source. As a result, those models may have different prediction accuracy. Based on these papers, we built a comprehensive analytical model for LPF-AM. The novelty of the model is based on the fact that it unifies the main physical changes of the whole process by coupling the attenuated laser power, the heated powder stream and the semi-infinite substrate with considering their concentration and intensity spatial distribution. In addition, the catchment efficiency model takes into account both the powder spatial distribution and the melt pool shape variation.

2. Analytical modelling

An analytical model for laser powder-fed additive manufacturing has been developed in this paper with the following assumptions:

(1) The lateral nozzle has a perfect circular outlet.
(2) The gas-powder flow is assumed as a steady state flow and the effect of the gravity and drag force are considered negligible. Thus, the powder stream has a uniform velocity in transverse direction which is assumed to be the same as the gas velocity near the nozzle outlet.
(3) The convection and radiation losses in the powder stream was not considered and the particles are isothermal with spherical geometry [16].
(4) Powder particles, impinging onto the molten pool, are considered effectively added to and mixed with the liquid flow on melt pool surface. It is required that the adhesion force $F_{ad}$is bigger than and the repelling force F_r ($F_{ad}/F_r > 1$) between the melt pool surface and the impinging particle. Lin [17] calculated the ratio of $F_{ad}/F_r = 100$ for stainless steel in coaxial LPF-AM, which testifies that the powder is effectively melted and attached onto the molten pool surface. The liquid phases will then rapidly mixed and become homogeneous due to the strong convection currents generated by the thermal gradients on melt pool surface (Marangoni convection/effect) [18,19].
(5) The thermo-physical properties for both powder and substrate are considered to be temperature independent. Average values over the temperature variation were considred in the model.

2.1. Powder spatial distribution

The schematic of LPF-AM is shown in Fig. 1. The laser beam scans in the positive y-direction with the process velocity$v$, and the origin of its coordinates is fixed at the center of the laser beam spot on the substrate. The nozzle has an inclined angle φ and distance H with respect to the substrate plane. The laser beam and the powder stream interact with each other after point P.

The powder concentration mode in the transverse direction was identified with Gaussian distribution by Lin [20] with both optical techniques and the theory of particles diffusion and convection in gaseous medium based on Fuchs's aerosols laminar flow. Optical luminance experimental analysis of Pinkerton's research [21] verified that the particles stream have Gaussian concentration profiles in the transverse plane. Yang [22] and Gangxian [23] also built the