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Full Length Article

Planning the process parameters for the direct metal deposition of functionally graded parts based on mathematical models

Jingyuan Yan[a,*], Ilenia Battiato[b], Georges M. Fadel[a]

[a] Department of Mechanical Engineering, Clemson University, Clemson, SC 29634, United States
[b] Department of Energy Resources Engineering, Stanford University, Stanford, CA 94305, United States

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ABSTRACT

During the past few years, the need for functionally graded material (FGM) parts has surfaced with the development of material science and additive manufacturing techniques. The Direct Metal Deposition (DMD) process, a metal based additive manufacturing technique, can locally deposit dissimilar metal powders to produce FGM parts. Yet inappropriate mixing ratio of materials without considering the influence of dilution and overlapping effects among layers and tracks and the variation of material properties can result in inaccurate material composition in the fabricated parts when compared to the desired compositions. Within such a context, this paper proposes a design method that links the process parameters to the desired composition of the part based on mathematical models. The proposed scheme is illustrated through a case study of fabricating an iron-nickel FGM part with three-dimensional composition variation. Using the proposed method, the process parameters can be planned prior to the manufacturing process, and the material distribution deviation from the desired one can be reduced.

1. Introduction and background

The fast-growing metal based additive manufacturing is being applied in increasingly diverse industry fields. The promising technologies include powder bed methods such as Selective Laser Melting (SLM) and Electron Beam Melting (EBM), and direct energy deposition methods such as Direct Metal Deposition (DMD) and Laser Engineered Net Shaping (LENS). The powder bed methods are preferred for their ability to fabricate beam or shell structures that need support during the process, whereas the direct energy deposition methods can deposit and melt powders where and when needed. Because of this, the potential of DMD will grow significantly with the ability to design and fabricate functionally graded materials (FGM).

An FGM part is a part with graded materials distribution, which can realize appearance and/or functionality that a homogeneous part cannot achieve. The DMD process can deliver dissimilar powders either via powders premixing [1–6], or via powder in situ mixing [7–10]. For the powder premixing of elemental powders blend approach, segregation effect of dissimilar powders due to the different densities and remixing effect within the powder mixer exist, which increases the composition control difficulty and reduces the deposition accuracy. Therefore, in this study, the focus is on the in situ mixing approach, where different powders are injected through different nozzles and mixed in the melt pool. The main advantage of this approach is that the powder composition can be adjusted on demand and ultimately as per the design requirements.

The schematic of the DMD working space is shown in Fig. 1, where the part being fabricated is an FGM part. Dissimilar powders are injected from different nozzles and mixed in the melt pool induced by the laser beam. The part is fabricated in a layer by layer and track by track manner (track is the name given to the material deposited and solidified by one pass of the laser), and the material composition is adjustable whenever needed. The specification of the part composition drives the control of the powder mixing ratio by regulating the powders feed rates (and possibly the laser energy and/or the scanning speed). It should be noted that the delay effect due to the length of the powder delivering hose and nozzles is to be considered by introducing a time delay.

Ever since multi-material deposition using the LENS^{TM} or DMD technology was attempted and published in the late 1990s [11], the investigation and fabrication of simple FGM parts have been implemented in a number of papers [12–20]. In order to fully take advantage of the potential of heterogeneity in objects, the ability to manufacture the material distribution and shape according to

* Corresponding author.
E-mail address: jingyuy@g.clemson.edu (J. Yan).

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Nomenclature

D	Dilution rate
S_1	Total cross-sectional area of the deposited layer
S_2	Cross-sectional area of the melted substrate
S_2	Groove between two adjacent tracks
O	Overlapping ratio
S_1'or S_1"	Cross-sectional area of the overlapping region between two adjacent tracks above substrate
S_2'or S_2"	Cross-sectional area of the overlapping region between two adjacent tracks below substrate
O_1 and O_2	Centers for the circular segments above the substrate surface
R	Radius of the circular segments above the substrate surface
O_1' and O_2'	Highest points for the circular segments
H	Layer height
$C_{i,dep}^{m,n}$	Deposition composition of element i in the mth layer nth track
$C_{i,pow}^{m,n}$	Instantaneous powder composition of element i in the mth layer nth track
$C_{i,sub}$	Concentration of element i in the substrate
$D_i^{m,n}$	Dilution rate between the element i in the mth layer nth track and the element below it
W	Width of track, melt pool width
W'	Overlapping distance between two adjacent tracks
η_a	Efficiency for laser absorption
η_d	Efficiency for powder deposition
η_m	Efficiency for melting
$\dot{V}_p$	Total powder volumetric feed rate
P_0	Total power in the laser beam
P	Attenuated laser power
ΔH_s	Melting enthalpy of the substrate material
ΔH_p	Melting enthalpy of the powder material
η_l	Absorptivity due to material optical property
η_n	Absorptivity due to the shadowing effect of powders
V	Laser scanning speed
α	Thermal diffusivity
ε_p	Molar absorptivity or extinction coefficient
r_p	Radius of the powder particles
ρ_p	Density of the powder particles
C_{pow}	Powder concentration/density in air
θ_1 and θ_2	Powder injection angles
φ	Powder jet divergence angle
w_1 and w_2	Diameters of the nozzles
r	Radius at waist of the gaussian laser
f	Shape factor of gaussian laser
ρ	Density of substrate material
c_p	Specific heat of substrate material
k	Thermal conductivity of substrate material
T	Substrate temperature
t	Time
T_∞	Ambient temperature
$\mathbf{n}$	Normal vector pointing outward from the substrate
ε	Emissivity of substrate
σ	Stefan-Boltzmann constant
h_c	Heat transfer coefficient
C_p^*	Equivalent latent specific heat of substrate
L_f	Latent heat of fusion of substrate
γ	Fraction of solid phase of substrate
ρ_{sol}	Density of solid and liquid phase of substrate
ρ_{liq}	Density of liquid phase of substrate
P_test	Attenuated laser power for testing
P_fix	Fixed attenuated laser power
$\dot{V}_{p_i}^{m,n}$	Powder feed rate at element i in the mth layer nth track
$V_i^{m,n}$	Laser scanning speed at element i in the mth layer nth track
L_x, L_y, L_z	The length, width, and height of the example block
T_{melt}	Melting temperature
P_{equal}	Equivalent attenuated laser power

a part's design is needed. Previous studies have shown that DMD and similar processes have the potential for fabricating FGM parts, and some of the research work has been well summarized by Qi et al. [21]. Many other publications are focused on the characterization of the FGM parts built by the DMD process. For example, Ocylok et al. used tensile tests and hardness tests to study the mechanical strength of the FGM parts made of Marlok and Stellite 31 powders [22]. Soodi et al. investigated the tensile strength and fracture mechanisms of FGM parts using different metal/alloy powders, i.e. 316 SS with 420 SS, Colmonoy6 with 316 SS, AlBrnz with 420 SS, and 316 SS with tool steel [23]. The effects of laser power and powder mass flow rates of SS316L and Inconel 718 on the microstructure and physical properties such as hardness, wear resistance, and tensile strength of FGM were discussed by Shah et al. [24]. The published results show the improvement of material properties when compared to a homogeneous material.

However, past work in FGM parts fabrication considered a uniform material in circular or straight track, allowing a composition change only at the next track/layer [20,22,24]. This constrains the DMD's potential of FGM parts manufacturing. To our knowledge, the investigation of composition change point by point has not been researched nor published. Meanwhile, despite the large number of reports on modeling and design of FGM parts, limited literature on the influence of the mixed/shared portion of a certain track/layer with its adjacent tracks/layers have been published. Moreover, the influence of the changing dilution rates and material properties during the process remained elusive when considering the design for manufacturing.

In this study, a methodology for planning the process parameters in DMD fabrication of FGM parts is proposed in order to understand the link between the desired material distribution and the process parameters. Mathematical models are derived and formed to aid the design process. The proposed scheme is illustrated through a design case study of fabricating an iron-nickel FGM part with three-dimensional composition variation.

2. Model based design methodology

2.1. Overall framework

The DMD process involves many complex physical phenomena. We first develop the mathematical models on which the design is based. The main overall assumptions for the model development are: 1) the powder particles that are injected into the melt pool do not have bouncing or splashing effect; 2) only phase changes are taken into consideration and chemical processes are not considered; 3) within the design space, the melt pool and the maximum temperature on the substrate is seen as in steady state and can solidify into perfect partial spherical shape; 4) after manufacturing one layer (with multiple tracks), the top of layer is considered to be flat (Fig. 5(a)); 5) the time interval between manufacturing adjacent layers/tracks is sufficiently large so that the heat accumulation from previous layers is negligible.