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Modeling of transport phenomena in direct laser deposition of metal matrix composite

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ABSTRACT

Direct laser deposition of metal matrix composite provides a very promising method to fabricate non-homogeneous material in one step directly from CAD drawings. During this process, reinforcing hard particle phase is mixed with the liquid matrix material to change the material property. Despite its usefulness, an understanding of interaction between the reinforcing particle and matrix material in the molten pool still remains as a challenge to determining the final properties of the fabricated composite. In this paper, distinct comprehensive modeling is presented to describe the complex transport phenomena during direct laser deposition of metal matrix composite. The molten pool thermal and fluidic behavior with the inter-phase coupling between particles and matrix material is modeled. To track the particle distribution, a species transport equation for particle mass fraction, as well as algebraic expressions considering possible different phase velocities, is combined with the other deposition governing equations. The mixture properties of composite are obtained by incorporating the volume fraction of each phase. The simulated average particle volume fractions agree with the experimental results and the model can be used to design the properties of the composite synthesised by the laser direct deposition process.

1. Introduction

Laser direct deposition of metal matrix composite (MMC) is a novel method of fabricating non-homogeneous parts directly from CAD drawings. During the process, reinforcing hard particles are mixed with liquified matrix material in the molten pool. After the laser moves away, a composite material is formed with the particles embedded in the deposited track due to solidification of the matrix. By combining appropriate materials, the properties such as specific modulus, strength and wear resistance of synthesised MMC can be improved [1]. Despite its usefulness, an understanding on how the reinforcing particles interact with the matrix material in the molten pool still remains a challenge to determining the final property of the synthesised composite, which is a function of resultant volume fraction of reinforcement [1]. Due to many parameters involved in the process, it is difficult to select optimal processing conditions for desired MMC properties. Therefore mathematical modeling is very important for a better understanding of the underlying physics and guiding the process design. Although there are a number of studies on the modeling of homogeneous material laser direct deposition [2–6] in the literature, modeling on deposition of particle reinforced composite is very rare.

Without introducing reinforcing particles into the molten pool, He and Mazumder [7] developed a three-dimensional (3D) self-consistent model to describe transport phenomena during a direct metal deposition process. However the effect of continual addition of mass and energy due to deposited powder was not rigorously considered. The particle transport in the laser induced molten pool was presented by a few modeling studies [8,9]. By assuming that the alloy particles move with the same velocity as that of the melt fluid, Raj et al. [8] modeled the transport phenomena during laser surface alloying. Although particles were tracked in the molten pool, they were considered melted simultaneously [8] without really reinforcing the material. Rohde et al. [9] presented a numerical model for the simulation of laser-induced surface modification processes of ceramics. The dispersion of reinforcing particles was modeled, but the particles are assumed to move at the same velocity of the melt again without considering possible relative motion between phases.

As seen from above discussion, a particle dispersion model for direct laser deposition processes is still lacking and it is important to develop such a model so that desired composite properties can be achieved. In this study, a novel 3D comprehensive model is developed to reveal the complex phenomena of the direct laser deposition of MMC, including mass addition, track interface evolution, reinforcing particle transport, fluid flow, heat transfer, melting and solidification process, with the incorporation of the distributed powder densities, velocities, and temperatures as input. The model addresses more complete physics by incorporating additional

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Nomenclature

A	Hamaker constant
A_h	convection coefficient
a	acceleration
c	heat capacity
$\vec{e}_x, \vec{e}_y, \vec{e}_z$	direction vector
F	free surface growth velocity
f	liquid mass fraction
$\vec{g}$	gravitational acceleration
g	liquid volume fraction
H	heaviside function
h	enthalpy
K	isotropic permeability
k	thermal conductivity
L_m	latent heat
l_p	distance between particles
$\widetilde{L}_m$	modified latent heat
M	mass concentration
M''	mass flux
$\vec{n}$	normal vector of free surface
p	pressure
q''	heat flux
r	radius or radial distance
$\dot{S}$	source term
T	temperature
T_0	ambient temperature
t	time
u, v, w	velocity
$\vec{V}$	velocity vector
x, y, z	coordinates

Greek symbols

α	particle volume fraction
θ	particle mass fraction
ρ	density
γ	surface tension
ε	radiation emissivity
ϕ	level set function
μ	dynamic viscosity
β	thermal expansion coefficient
κ	interface curvature
σ	Stefan–Boltzmann constant
δ	delta function
ψ	sphericity

Subscripts

com	composite
enthalpy	energy equation
g	gas
i	direction
l	laser
ℓ	liquid
liq	liquidus
m	matrix metal
mass	continuity equation
mom	momentum equation
p	particle
r	reference
s	solid
sol	solidus
VDW	Van der Waals

source terms into a set of governing equations, which will lead to more accurate prediction of clad dimensions. An improved level-set method is proposed to track the evolution of free liquid/gas interface during the deposition process. To accurately predict the particle distribution, a distinct particle transport equation is developed and coupled with the other governing equations. In addition, the possible relative motion between particle and matrix phase is also considered.

2. Model development

In this study, laser engineered net shaping (LENS™) [6] is used for the study of MMC direct laser deposition. The 316L steel powder thoroughly pre-mixed with titanium carbide (TiC) was used. The mixture powder was supplied through four radially symmetrical powder flow nozzles by the carrier gas and fed into a laser focused spot where the 316L steel particles melt as a bonding matrix while TiC particles remain solid and get mixed in the molten pool. After laser scanning, a solidified MMC track is formed with TiC particles trapped inside. The corresponding schematic of the process is illustrated in Fig. 1. The fiber laser beam is Gaussian with a half divergence angle of 2.7° and focused onto a 0.5 mm spot at 9.525 mm down the nozzle tip. Some assumptions were made in the model including incompressible liquid flow in the molten pool while considering velocity fluctuation, immediate steel powder melting at the free surface, and and neglecting the effect of shielding gas pressure and turbulence on the molten pool [6].

The distributed powder flow densities, velocities and temperatures were predicted by a powder flow model [10] and incorporated as inputs into the current deposition model. To accurately model the continuous mass addition, evolution of the liquid–gas interface (free surface), molten pool fluid motion, reinforcing particle transport, heat transfer, melting and solidification, a distinct set of governing equations for the transport behavior in MMC direct laser deposition are presented in this section.

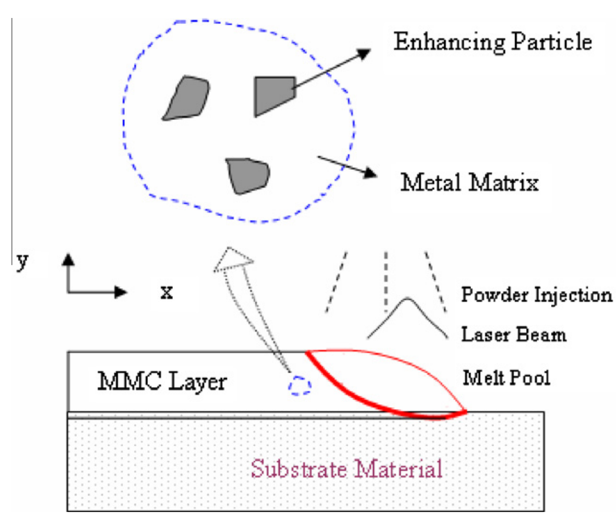

Fig. 1. Schematic of MMC direct laser deposition.

2.1. Mass addition

To precisely predict the continuous mass addition during MMC deposition processes, an enhanced mass conservation equation is developed as in [5,6]: