International Journal of Heat and Mass Transfer 115 (2017) 80–91

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Evaluation of the relevance of melt pool dynamics in Laser Material Deposition process modeling

Jon Iñaki Arrizubieta [a,*], Aitzol Lamikiz [a], Fritz Klocke [b], Silvia Martínez [a], Kristian Arntz [b], Eneko Ukar [a]

[a] Department of Mechanical Engineering, University of the Basque Country UPV/EHU, c/ Plaza Torres Quevedo 1, 48013 Bilbao, Spain
[b] Fraunhofer Institute for Production Technology IPT, Steinbachstrasse 17, 52074 Aachen, Germany

ARTICLE INFO

Article history:
Received 15 March 2017
Received in revised form 5 June 2017
Accepted 4 July 2017
Available online 14 July 2017

Keywords:
Laser Material Deposition
LMD
Simulation
Melt pool fluid-dynamics

ABSTRACT

The melt pool dynamics consideration in the numeric modeling of the Laser Material Deposition (LMD) process can be enormously difficult and expensive, especially if this calculation is not strictly necessary. The increased cost comes mainly from the necessity of considering a higher number of input parameters into the model in addition to the computational cost. Therefore, an analysis of the influence of the melt pool dynamics in a LMD model and its impact on the accuracy is presented. For this purpose, a numeric model that simulates the melt pool fluid-dynamics has been developed and experimentally validated for different situations. After a detailed analysis of the results, an exponential formula based on the response surface methodology (RSM) that quantifies the influence of the fluid-dynamic phenomena inside the melt pool has been obtained. The main conclusion of the present work is that the LMD process can be addresses as a thermal problem without considering the melt pool dynamics and without losing accuracy for a certain window of process parameters, what reduces the computational cost and will allow an easier integration of the model in CAE tools for process simulation.

1. Introduction

The Laser Material Deposition (LMD) is an additive manufacturing process based on the generation of a melt pool on the surface of a substrate, while filler material is added in wire or powder form [1]. As the laser beam focusing position moves, the resulting combination of substrate and filler material solidifies almost instantly due to the high cooling rates, which values can be up to 10^3–10^5 K·s^{-1} [2], and consequently, high quality metallurgical bonding is obtained. The LMD process is gaining relevance in industry because of its advantages over other additive techniques such as arc welding or thermal spray [3]. Some authors ensure that the LMD process provides better quality coatings, together with a minimal dilution, minimal distortion and good surface quality [4]. Thanks to these advantages, as Wissenbach stated, LMD has become a reference technique in many companies for applying wear and corrosion protective layers on metallic workpieces as well as for the repair of high added value components [5].

Many authors have focused their efforts on modeling the LMD process and Pinkerton carried out a depth review of the most relevant works in this field [6]. Regarding material addition, most authors assume the statement that all powder particles that fall inside the melt pool contribute to the clad generation [7,8]. In the same direction, the size of the melt pool is determined by the temperature field in the substrate and therefore the interaction between the laser beam and the substrate must be properly modeled in order to obtain an accurate LMD model [9]. Therefore, it is really important to model properly the interaction between the laser beam and the substrate [10].

Typically, with the aim of reducing the computational cost and facilitate the programing, the problem is addressed in a simplified way. Typical assumptions considered by different authors are the omission of the material displacement inside the melt pool [11–16], or the implementation of an enhanced thermal conductivity coefficient for the heat transfer inside the melt pool [17,18]. Even authors that consider the movement of the molten material introduce simplifications such as the supposition of a laminar flow with a viscous incompressible heat conducting fluid [19] or the assumption that the surface of the substrate remains flat and no interface movement occurs [20]. More complex models that include the movement of the molten material and the displacement of the surface interface have been presented [21,22] where the geometry of the melt pool is modeled with high accuracy.

However, it is difficult to quantify the impact of these assumptions on the accuracy of the resulting model. Moreover, most of

* Corresponding author at: Department of Mechanical Engineering, University of the Basque Country (UPV/EHU), Faculty of Engineering in Bilbao, c/Plaza Torres Quevedo 1, 48013 Bilbao, Spain.
E-mail address: joninaki.arrizubieta@ehu.eus (J.I. Arrizubieta).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.07.011
0017-9310/

Nomenclature

u	fluid velocity in the X axis direction	T	time variable
v	fluid velocity in the Y axis direction	Δt	time step
w	fluid velocity in the Z axis direction	t_{int}	powder particle - laser beam interaction time
U	absolute fluid velocity	P	laser power
Δx	element size in the X axis direction	P_{att}	laser power attenuation
Δy	element size in the Y axis direction	q_{laser}	laser beam intensity
Δz	element size in the Z axis direction	q_{losses}	energy losses due to radiation and convection
ρ	material density	r_l	laser beam radius in the focal plane
p	pressure value	α	absorptivity
μ	material viscosity	h	convection coefficient
$\underline{g}$	gravitational acceleration constant	ε	emissivity
$\underline{e}$	Z+ direction unitary vector	σ_b	Stefan-Boltzmann coefficient
γ	volume fraction (solid/liquid)	t_{int}	interaction time between laser beam and powder particles
σ	surface tension	$L_{average}$	average distance that powder particles travel through the laser beam
$\frac{d\sigma}{dT}$	surface tension variation regarding the temperature	θ	laser beam semi-angle
κ	surface curvature	δ	angle between the tangent of the surface and the horizontal
$\vec{n}$	vector normal to the surface (solid/liquid – gas interface)	fpp	focal plane position
β	coefficient of liquid thermal expansion	v_p	powder particle average velocity at the nozzle exit
c	specific energy	r_{pm}	powder particle average radius
L	latent heat of fusion	S_p	powder particle projected area
k	heat conductivity	m_p	powder particle average mass
T	temperature	MP	melt pool fluid-dynamic relevance coefficient
$T_{solidus}$	solidus temperature	I	laser beam average intensity
$T_{liquidus}$	liquidus temperature	v_f	LMD machine feed rate
T_{∞}	room temperature	$\dot{m}$	powder mass rate
$T_{initial}$	powder particle preheating temperature		
T_p	temperature of the powder particles when they enter into the melt pool		

LMD models do not implement melt-pool dynamics, but do not have evaluated neither the relevance of considering the melt pool fluid-dynamics, nor the impact of their omission in the accuracy of the model. On the other hand, if these fluid-dynamic phenomena are not considered, the resulting computational cost of the model is considerably reduced and this could enable their implementation in CAD/CAM/CAE tools [23]. Nevertheless, a sufficient level of accuracy must be also maintained.

Consequently, the present work focuses on the analysis of the relevance of considering or neglecting the melt pool fluid-dynamics in a LMD model and its influence on the accuracy of the numerical model. For this purpose, a series of experimental tests have been performed in order to validate the model and determine the influence of the movement of the molten material in the melt pool.

2. Methodology proposed to analyze the influence of the fluid-dynamic phenomena inside the melt pool

The used model has been entirely programmed in Matlab environment and the following deployed methodology has been applied for the analysis of the relevance of the fluid-dynamic phenomena inside the melt pool, see Fig. 1. First of all, a model that simulates the melt pool fluid-dynamic phenomena under a static laser beam has been developed based on the classic SIMPLE algorithm developed by Patankar [24].

Once the numerical model has been experimentally validated for simulating the melt pool under a static laser beam, the model has been adapted for simulating the full LMD process. The LMD model enables to simulate the material deposition under the consideration or the omission of the fluid-dynamic phenomena. Simultaneously, a series of experimental tests have been carried out in order to validate the model and analyze its accuracy. Finally, an evaluation of the relevance of the melt pool fluid-dynamics on the LMD process is presented.

3. Description of the simulation model

As it has been mentioned in the previous section, the model has been developed in 3 steps: First, a model that simulates the melt pool dynamics under a static laser beam has been completed. Afterwards, a complete LMD model, including the melt pool dynamics consideration, has been performed. Finally, a simplified model of LMD process has been carried out, neglecting the effect of the fluid dynamics into de melt pool.

3.1. Melt pool dynamics governing equations

The proposed model is based on a classical solution, which solves continuity (2), momentum (3) and energy conservation (6) equations in order to obtain the pressure, velocity and temperature fields of each element respectively. Both, conduction and diffusion have been considered as heat transfer mechanisms inside the substrate. Furthermore, the Volume of Fluid (VOF) equation (9) has been solved in order to simulate the material flow inside the control volume and enable the liquid-gas boundary movement when the process requires it.

All the analyzed variables are assumed to have a linear variation during the time interval "Δt". Moreover, as it is shown in Eq. (1), a fully implicit scheme has been adopted ($f = 1$), this means that for each time step the value of the variable for the next time step is calculated.

$$\int_t^{t+\Delta t} \phi_P \cdot dt = [f \cdot \phi_P + (1-f) \cdot \phi_P^0] \cdot \Delta t = \phi_P \cdot \Delta t \quad (1)$$