Materials and Design 55 (2014) 482–491

Contents lists available at ScienceDirect

Materials and Design

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

Thermal behavior and densification mechanism during selective laser melting of copper matrix composites: Simulation and experiments

Donghua Dai, Dongdong Gu *

College of Materials Science and Technology, Nanjing University of Aeronautics and Astronautics (NUAA), Yudao Street 29, 210016 Nanjing, PR China

ARTICLE INFO

Article history:
Received 11 August 2013
Accepted 1 October 2013
Available online 14 October 2013

Keywords:
Numerical simulation
Additive manufacturing
Selective laser melting
Metal matrix composites
Marangoni flow

ABSTRACT

Simulation of temperature distribution and densification process of selective laser melting (SLM) WC/Cu composite powder system has been performed, using a finite volume method (FVM). The transition from powder to solid, the surface tension induced by temperature gradient, and the movement of laser beam power with a Gaussian energy distribution are taken into account in the physical model. The effect of the applied linear energy density (LED) on the temperature distribution, melt pool dimensions, behaviors of gaseous bubbles and resultant densification activity has been investigated. It shows that the temperature distribution is asymmetric with respect to the laser beam scanning area. The center of the melt pool does not locate at the center of the laser beam but slightly shifts towards the side of the decreasing *X*-axis. The dimensions of the melt pool are in sizes of hundreds of micrometers and increase with the applied LED. For an optimized LED of 17.5 kJ/m, an enhanced efficiency of gas removal from the melt pool is realized, and the maximum relative density of laser processed powder reaches 96%. As the applied LED surpasses 20 kJ/m, Marangoni flow tends to retain the entrapped gas bubbles. The flow pattern has a tendency to deposit the gas bubbles at the melt pool bottom or to agglomerate gas bubbles by the rotating flow in the melt pool, resulting in a higher porosity in laser processed powder. The relative density and corresponding pore size and morphology are experimentally acquired, which are in a good agreement with the results predicted by simulation.

1. Introduction

In recent years, there have been a lot of focuses on the fabrication of copper matrix composites (CMCs) due to their excellent electrical properties, thermal conductivity and good resistance to oxidation [1–3]. WC, due to its high hardness, good wear resistance and high elastic modulus, is regarded as a good reinforcement material for Cu [1]. Thus WC/Cu composites are the suitable candidates for a typical use in high-voltage electrical applications [2]. Generally, the WC/Cu parts are fabricated using common casting and powder metallurgy (PM) methods, which need expensive and dedicated tools such as mould or dies [4,5]. However, the requirement of processing temperatures being significantly above the melting point of copper (1390 K) is the shortcoming of the conventional processes for WC/Cu composites [2], which may result in the abnormal grain growth and accordingly produces the poor mechanical properties. Therefore, it seems that the conventional processing approaches have the limited capacity to meet the high industrial requirements for CMCs parts. Meanwhile, parts with complex geometrical shapes cannot be fabricated easily via the conventional methods. Therefore, both demands for obtaining complex features and high comprehensive mechanical properties are expected to be satisfied by using other novel processing technique.

Selective laser melting (SLM), as a newly developed additive manufacturing (AM) technique, enables the quick fabrication of three-dimensional parts with any complex shapes directly from metal powder [6–10]. The SLM process creates parts in a layer-by-layer fashion by selectively melting thin layers of loose powder with a high energy laser beam [11,12]. This technique competes effectively with other conventional manufacturing processes as the part configuration is complex and the production run is not large. Although recent advances in SLM have considerably promoted this technology, this method essentially relies on empirical, experimental knowledge and still lacks a strong theoretical basis [13]. This may be attributed to the complex metallurgical process of SLM, which exhibits multiple modes of heat, mass and momentum transfer [14,15]. One of the uncontrollable defects of SLM process is high porosity, which is detrimental to the final mechanical properties of SLM parts [16,17]. Many investigations, aiming to obtain a high densification level for SLM parts, have been reported. Zhang et al. [18] studied the effects of processing parameters on properties of SLM Mg–9%Al powder mixture. It was found that porosity of samples was highly dependent on the energy density,

* Corresponding author. Tel./fax: +86 25 52112626.
E-mail address: dongdonggu@nuaa.edu.cn (D. Gu).

0261-3069/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.matdes.2013.10.006

Nomenclature

A	laser absorptivity of the powder	T_{ref}	reference temperature, K
C_p	specific heat at constant pressure, J/(kg K)	v_b	velocity of the gaseous bubble, m/s
D_p	average diameter of the powder particles, m	$\vec{v}$	overall velocity vector, m/s
E	total energy, J	u, v, w	velocity magnitude, m/s
$\vec{F}$	force vector	x, y, z	coordinates, m
g	gravitational acceleration, m/s^2	α	volume fraction of the gas phase
h	sensible enthalpy, J/kg	α_i	volume fraction of each phase
h_c	convective heat transfer coefficient, W/(m^2 K)	γ	surface tension, N/m
h_{ref}	reference enthalpy, J/kg	ε	radiation emissivity
H	enthalpy of the material, J/kg	κ	thermal conductivity of the powder bed, W/(m K)
ΔH	latent heat of the phase change, J/kg	κ_s	thermal conductivity of the solid, W/(m K)
p	pressure, Pa	κ_{eff}	effective thermal conductivity of liquid–solid–gas multi-phases, W/(m K)
P	laser power, W	κ_f	thermal conductivity of the fluid, W/(m K)
S_h	source item of the radiation and any other volumetric heat sources	κ_r	thermal conductivity due to the radiation among particles, W/(m K)
S_H	source item of the energy conservation equation	μ	dynamic viscosity, Pa s
S_x, S_y, S_z	source item of the momentum conservation equation	ρ	density, kg/m^3
S_{α_i}	mass source for each phase	ρ_i	density of each phase, kg/m^3
t	time, s	σ_e	Stefan–Boltzmann constant
T	temperature, K	ω	radius of the Gaussian laser beam, m
T_∞	ambient temperature, K		
T_p	temperature of the powder particles, K		

and eventually the densification mechanism during SLM was established by the authors. Hazlehurst and his coworkers [19] focused on the design and fabrication of cobalt chrome molybdenum cellular structures with different porosities via SLM. It was shown that mechanical properties were significantly influenced by the volumetric porosity. Saha et al. [20] investigated the crack density and wear performance of Al-based metal matrix composite fabricated by direct metal laser sintering (DMLS) AM process. The size and volume fraction of SiC reinforcing particles were varied to analyze the density and wear behavior of laser processed composites. Ferrar et al. [21] studied the effect of inert gas flow during the SLM process on the mechanical performance of SLM parts, in order to enable the production of desired components with a greater reproducibility.

Although the porosity rate can be decreased by optimizing laser parameters and improving scanning strategy during SLM, the inner porosity normally cannot be completely eliminated [22,23]. To date, little work has been focused on the effects of gas phase in the starting powder system on the densification behavior of powder under various SLM processing conditions. Furthermore, the unique metallurgical process of SLM, e.g. the presence of significant Marangoni effect and the super high undercooling degree, significantly impedes the systematic investigation of the densification activity of the melt pool during SLM process. Therefore, it is of great importance and necessity to find a feasible method to quantitatively reveal the densification behavior of SLM-processed powder and to predict the undesired porosity appeared in the finally solidified melt.

In this work, the numerical simulation regarding the influence of the linear energy density (LED) of laser beam on the melt pool dynamics and densification mechanisms during SLM of WC/Cu powder system was presented, using Fluent 6.3.26 commercial finite volume method (FVM) software. The fluid flow driven by surface tension gradient and gravity forces was considered in the physical model and the temperature distribution, melt pool dimensions, behaviors of bubbles and Marangoni convection were simulated. Furthermore, the relative densities of SLM parts obtained by numerical simulation were compared with those acquired via experiments, in order to testify the accuracy of the developed simulation model and obtain reasonable SLM processing conditions to produce high density WC/Cu parts.

2. Model descriptions

Fluent 6.3.26 software, which enables simulation of processes with molten metal flow and behavior of the gaseous bubbles, is introduced to simulate SLM process. To simplify the problem, the following assumptions are made in this study: (1) The melt in the molten pool is assumed to be laminar and incompressible homogeneous Newtonian fluid; (2) Except thermal conductivity, surface tension and viscosity, some other thermal physical constants are considered to be temperature independent; and (3) The metal vaporization is ignored.

2.1. Physical model

The schematic of SLM physical model is depicted in Fig. 1. In simulation the laser beam is defined as a heat flux, $q_{(x,y,z,t)}$, with a Gaussian power distribution as an incoming heat source, which moves at a constant rate along the X-axis. The geometry of this source is assumed by the absorption phenomenon in the skin layer.

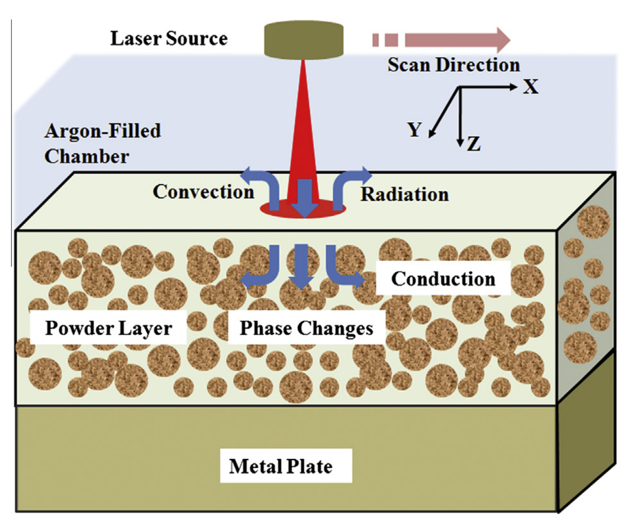

Fig. 1. Schematic of SLM physical model.