International Journal of Heat and Mass Transfer 73 (2014) 429–437

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Modeling and simulation on long pulse laser drilling processing

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ARTICLE INFO

Article history:
Received 19 September 2013
Received in revised form 7 February 2014
Accepted 13 February 2014
Available online 14 March 2014

Keywords:
Laser drilling
Numerical simulation
Drilling velocity
Aspect ratio
Melt ejection
Keyhole quality

ABSTRACT

Combining the modified level-set method a 2D model is developed to simulate the laser drilling process on aluminum slab with millisecond pulsed laser. By utilizing equivalent specific heat capacity and adding source terms of gas dynamics, phase transition is modeled. Modified level-set method is developed in order to trace the liquid–gas interface as well as consider mass loss during evaporation and boiling. The possible effects which can impact the dynamic behavior of the keyhole are taken into account, containing gravity, recoil pressure of the metallic vapor, surface tension, and Marangoni effect. Based on such model the impacts of laser fluence and pulse duration on keyhole width and depth, average drilling velocity, morphology and quality, melt ejection mode transition as well as velocity of melt ejecta are investigated. Compared with some corresponding experiment results, the validity of the established model is verified and the mechanisms of phenomena during laser drilling are analyzed.

1. Introduction

Since the emergence of the first laser, its application has been an appealing and prevailing research field among researchers, which includes welding, cutting, ablation and so on. As a major application in processing industry like aerospace and automobile industry, interests in laser drilling have been escalated due to the growing number of scientific and manufacturing applications utilizing various kinds of high-power laser.

Laser drilling is a complicated process, accompanying with heat conduction, melting, evaporation, boiling, melt ejection, plasma and even the phase explosion. Therefore experiments alone are far insufficient from revealing the mechanism of the interaction between laser and materials. With the development of the computer, numerical simulation has become a powerful tool to help researchers discern the mechanisms behind the phenomena. In the past several decades numbers of models and experiments related to laser drilling have been reported [1–16]. Although the early work of developed models [1,2,16] were usually one dimensional, analytical and restricted ones, the drilling velocity, drilling efficiency, the position of the evaporation front, evaporation speed and melt ejection velocity were well predicted, setting up the foundation for the following research. After all such kinds of model are not suitable for complicated situations like intensive boiling companying with melt ejection, therefore numerical simulation is needed. Yilbas and Sami [7] studied liquid ejection and possible nucleate boiling mechanisms in the laser drilling process on copper and nickel experimentally and numerically. Trippe et al. [8] and Shuja and Yilbas [9] modeled single pulse drilling process on metals with a fixed free surface. Voisey et al. [10,11] researched the phenomenon of melt ejection during laser drilling of metals by experiments and carried out a novel method to measure the velocity of the melt ejecta. While going further more on the path of simulation of laser drilling process, it still has limitation and lacks of relative completeness, such as the tracking of free surface. Such obstacle has been overcome after developing of mathematical methods, saying moving mesh (ALE), Volume of Fluid (VOF), level-set and so on. Geiger et al. [5] established a 3D transient model of keyhole and melt pool dynamics in laser beam welding, using VOF method to track the free surface of the vapor–liquid interface. Ganesh et al. [12–14] established a 2D symmetrical model to study the process of melting and re-solidification during laser drilling, using VOF method to track the free surface. Ahn and Na [15] simulated nanosecond pulsed laser ablation process for semi-transparent material by combining VOF method and ray tracing method in a 3D model. Ki et al. [3] modeled high-density laser–material interaction by using fast level set method. The surface tension is not taken into consideration. Han et al. [4] and Han and Liou [6] also utilized the level set method to model pool thermal behavior, the geometry of the melt and investigated the laser mode influence on the melt pool. In these models, on one hand, the phase change of vaporization is not completely considered. We believe that just using the heat loss caused by evaporation as the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.02.037
0017-9310/

Nomenclature

A_{mush}	mushy zone constant
B	liquid volume fraction
C_p	specific heat capacity
C_{pair}	specific heat capacity of air
C_{pAl}	specific heat capacity of aluminum
$C_{pAl,eff}$	equivalent specific heat capacity of aluminum
E	laser peak energy
F_{vol}	body force
h	heat transfer coefficient
i	unit vector on x axis
I	identity matrix
j	unit vector on y axis
k	heat conductivity
k_B	Boltzmann constant
L_m	latent heat of fusion
L_v	latent heat of evaporation,
$\dot{m}$	removal rate of evaporation
$M_{al,mole}$	molar mass of the aluminum
$M_{al,molecular}$	molecular mass of aluminum
n	normal vector
p	pressure
P_{amb}	ambient pressure
P_{recoil}	recoil pressure
P_{sat}	saturated pressure
r_0	laser spot radius
R	universal gas constant
S	laser heat source
S_0	laser peak power
t	simulation time
t_p	laser pulse duration
T	temperature
T_0	initial temperature
T_b	boiling point
T_m	melting point
u	fluid velocity
V_e	recession speed of the vaporization front
V_f	volume fraction
x, y	cartesian coordinate system

Greek symbols

γ	level-set parameter
ε	level-set parameter
δ	delta function
δT_m	temperature transition zone half width (melting)
δT_b	temperature transition zone half width (evaporation)
ϕ	level-set function
α	absorptivity of aluminum on 1064nm laser
ξ	surface emissivity
κ	curvature radius
μ	dynamic viscosity
μ_{air}	dynamic viscosity of air
μ_{Al}	dynamic viscosity of aluminum
ρ	mass density
ρ_{air}	density of air
ρ_{Al}	density of aluminum
ζ	small number
σ	surface tension coefficient

Subscripts

L	liquid
v	vapor

boundary condition is far more insufficient from reflecting phase transition of vaporization and even more intense boiling effect. On the other hand, above mentioned surface tracking methods also have some demerits themselves.

In this paper firstly we present a 2D model of long pulsed laser drilling process on Aluminum, considering the phase change of both melting and vaporization and possibly primary driving forces that could influence the drilling process as well as combining modified level-set method for the purposes of tracking the liquid–vapor interface and offsetting mass loss caused by intense evaporation. Then the results of the influence of laser parameters based on such model are compared with the experiment data for the purposes of both verifying the validity of the model and analyzing the possible mechanisms of the phenomena involved in laser drilling process.

2. Physical model and mathematical formulation

In our previous work [27] the 2D model was described in detail. Therefore it is briefly reviewed below. The dimension of the model is showed in Fig. 1, and many assumptions are made as follows for simplifying the calculation:

(1) The flow of liquid metal in the melt pool is treated as incompressible Newtonian laminar flow.
(2) The surrounding air is also treated as incompressible laminar flow [17].
(3) Knudsen layer is ignored.
(4) Metallic vapor is regarded as ideal gas and transparent to the incident laser beam.
(5) Plasma formation and multiple reflection are not taken into consideration.
(6) The boiling point of the material is independent to the pressure.

2.1. Governing equations

When the laser beam is irradiated on the surface of Aluminum slab, the target and the surroundings are heated by heat conduction, heat convection, thermal radiation and so on. With the increase of temperature, melting occurs followed by vaporization, melt ejection, boiling and forming of keyhole with the help of material removal and recoil pressure determined by the absorbed laser energy. In order to interpret the interaction mechanism between laser and substrate, the general form of governing equations for the conservation of mass, momentum and energy, used in the whole computational domains, can be expressed in the following form:

$$\nabla \cdot \vec{u} = 0 \tag{1}$$

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho(\vec{u} \cdot \nabla)\vec{u} = \nabla \cdot \left[-pI + \mu\left(\nabla\vec{u} + (\nabla\vec{u})^T\right)\right] + \rho\vec{g} + \overrightarrow{F}_{vol} \tag{2}$$

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{u} \cdot \nabla T = \nabla \cdot (k\nabla T) \tag{3}$$

where $\vec{u}$ is the velocity, μ, ρ, C_p and k are the dynamic viscosity, density, specific heat capacity and heat conductivity of the whole