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Melt flow and heat transfer in laser drilling

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ABSTRACT

During the laser drilling process the recoil pressure drives melt flow and affects the heat transfer and material removal rate. To get a more realistic picture of the melt flow, a series of differential equations are formulated here that govern the process from pre-heating to melting and evaporation. In particular, the Navier–Stokes equation governing the melt flow is solved with the use of the boundary layer theory and integral methods. Heat conduction in solid is investigated by using the classical method with the corrections that reflect the change in boundary condition from the constant heat flux to Stefan condition. The dependence of saturation temperature on the vapor pressure is taken into account by using the Clausius–Clapeyron equation. Both constantly rising radial velocity profiles and rising-fall velocity profiles are considered. The proposed approach is compared with existing ones. In spite of the assumed varying velocity profiles, the proposed model predicts that the drilling hole profiles are very close to each other in a specific super alloy for given laser beam intensity and pulse duration. The numerical results show that the effect of melt flow on material removal can be ignored in some cases. The findings obtained from the current work provide a better understanding of the effects of melt flow and vaporization on the laser drilling profile evolution, and could improve the solid material removal efficiency.

1. Introduction

There are two major mechanisms that control the material removal in the process of laser drilling: (1) melt evaporation, and (2) melt expulsion by the vaporization-induced recoil force. It is generally thought that melt removal dominates if an assisting gas is applied on the melt surface when the melt surface temperature does not significantly exceed the melting point and the evaporation rate is low enough not to produce a noticeable recoil pressure. In the cases where there is no assisting gas involved, melt expulsion varies with the recoil pressure, which is highly dependent on the surface temperature. At a high surface temperature, the melt removal due to evaporation may exceed that by the hydrodynamic mechanism due to the recoil force. In an early simulation, a significant portion of the absorbed laser intensity was found to be taken away by the melt flow from the heat interaction zone [1]. Due to the difficulty in directly measuring the interface geometry and the temperature and recoil pressure at the melt-vapor interface, the portion of the melt removed by the recoil-force-driven flow cannot be quantitatively determined with existing experimental capabilities.

Considerable research has been carried out to develop a theoretical model for predicting the laser drilling response. Assuming a constant laser beam intensity profile, von Allmen analyzed the drilling velocity and drilling efficiency by using a one-dimensional (1-D) transient gas dynamic model [2]. Chan and Mazumder [3] developed a 1-D steady state model to incorporate liquid expulsion, but the 1-D assumption is not suited for the hole drilling with high aspect ratio and the drilling process is transient. Kar and Mazumder [4] extended the model to two-dimensional (2-D) cases in which melt expulsion was not considered. Armon et al. formulated a 1-D metal drilling problem based on the enthalpy balance method and solved the problem by using the Crank-Nicholson method [5]. They also conducted an experimental investigation on metal drilling with a CO_2 laser beam and analyzed the experimental results by using their theoretical model [6]. A more rigorous treatment of melt expulsion was presented by Ganesh et al. [7], which employed a 2-D transient generalized model and incorporated conduction, convection and phase change heat transfer

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Nomenclature

a	dimensionless curvature parameter of solid–liquid interface
c_{pl}	specific heat of the liquid [J kg^{-1} K^{-1}]
c_{ps}	specific heat of the solid [J kg^{-1} K^{-1}]
g	dimensionless melt layer thickness, normalized by laser beam radius
h_{ls}	latent heat of melting [J kg^{-1}]
h_{lv}	latent heat of vaporization [J kg^{-1}]
H_{lv}	dimensionless latent heat of vaporization, $\frac{h_{lv}}{R_g T_{sat0}}$
I_0	laser intensity at the center [W m^{-2}]
$I^{'}$	revised dimensionless laser intensity at the center for temperature calculation, $\frac{I_0}{p_0 h_{lv}}\sqrt{\frac{2\pi R_g T_{sat0}}{M}}$
j_v	is the molar flux of vaporization [kg s^{-1}]
k_l	thermal conductivity of liquid [Wm^{-1} K^{-1}]
k_s	thermal conductivity of solid [Wm^{-1} K^{-1}]
k	ratio of thermal conductivity of liquid over solid, $\frac{k_l}{k_s}$
$k^{'}$	dimensionless coefficient, $\frac{k_l(T_{sat0}-T_m)}{RI_0}$
M	molar mass of the gas evaporated from the melt [kg mol^{-1}]
N_i	dimensionless laser intensity of laser beam, $\frac{RI_0 c_{pl}}{h_{lv}k_l}$
N_α	thermal diffusivity ratio, $\frac{\alpha_s}{\alpha_l}$
N_c	specific heat ratio, $\frac{c_{ps}}{c_{pl}}$
p_c	vapor pressure at the center of laser beam
Pr	Prattle Number, $\frac{\mu}{\rho\alpha_l}$
p_0	vapor pressure at saturation temperature, 1.013×10^5 Pa
R	Gauss radius of laser beam, defined as the intensity reduced to *1/e* of that at the central point [m]
R_g	gas constant of the metal vapor [J kg^{-1} K^{-1}]
R_h	latent heat ratio, $\frac{h_{lv}}{h_{ls}}$
Sc	subcooling parameter, $\frac{c_{ps}(T_m-T_i)}{h_{ls}}$
Ste	Stefan number, $\frac{c_{pl}(T_{sat0}-T_m)}{h_{ls}}$
T_i	initial temperature of the solid [K]
T_m	melting temperature at solid–liquid interface [K]
T_{sat0}	saturation temperature at pressure p_0, [K]
T_{sat}	saturation temperature at pressure p, [K]
t_p	pulse on time, [s]
U	dimensionless radial velocity in the free flow
V	dimensionless vertical velocity in the free flow
V_v	vapor velocity at the melt surface
u	tangential velocity [m s^{-1}]
v	normal velocity [m s^{-1}]
α_l	thermal diffusivity of melt, $\frac{k_l}{\rho c_{pl}}$
θ_s	dimensionless temperature in solid, $\frac{T_s-T_m}{T_{sat0}-T_m}$
θ_l	dimensionless temperature in liquid, $\frac{T_l-T_m}{T_{sat0}-T_m}$
θ_i	dimensionless initial temperature of solid, $\frac{T_i-T_m}{T_{sat0}-T_m}$
θ_m	ratio of melting temperature over saturation temperature, $\frac{T_m}{T_{sat0}}$
θ_{sat}	dimensionless temperature at the melt-vapor interface, $\frac{T_{sat}-T_m}{T_{sat0}-T_m}$
τ	dimensionless time, $\frac{t\alpha_l}{R^2}$

during laser drilling; this model, however, is computationally demanding. Zhang and Faghri developed an analytical model to study the effect of solid conduction on the material removal rate and phase change at interfaces [8]. In this model, the melt flow effect on heat transfer is neglected. Zhang et al. developed a 2-D transient model, in which a Knudsen layer was considered at the melt-vapor front without including the melt flow effect [9]. Pastras et al. analyzed the material removal efficiency by assuming linear temperature profiles in solid, liquid and vapor [10], with an implicit assumption that the melt flow does not cause any disturbance on temperature gradient.

The melt flow effect has been considered in some existing models. For example, the model developed by Semak and Matsunawa [1] and a later version adapted by Low et al. [11] to include the melt flow effect with an assisting gas on laser drilling are both steady-state based on conservation of mass and energy. Semak and Matsunawa attempted to evaluate the effect of recoil pressure during the melt ejection process, and their model is based on the assumption of a free flow layer of melt under the laser beam of hat-top shaped intensity profile [1]. They also considered the temperature-dependent pressure (but not Clausius–Clapeyron equation). Ng et al. developed a model of laser drilling incorporating the effect of using oxygen as an assisting gas. They assumed that the melt front propagates with an averaged velocity and the averaged melt thickness is determined via dividing the thermal diffusivity of the melt by the averaged propagating velocity [12]. Zeng et al. developed a 2-D analytical model for optical trepanning assuming that vaporization rate is negligible [13]. Collins and Gremaud developed a simple 1-D model by cross-section averaging while neglecting the contribution of the radial flow velocity component [14]. It is worthy to note that the melt flow models developed in [1,2,12] and the latest simulation by Semak and Miller [15] all assume a hat-top-shaped intensity profile. The assumption about the laser beam intensity profile directly affects the conclusion about the melt flow [16–18]. Using the hat-top profile, the melt surface temperature could be assumed to be constant, though a rapid change occurs at the margin of the melt. If the melt flow is further assumed to be free of shear traction, the recoil pressure can also be assumed to be constant, which leads to an overestimate of the role of melt expulsion. Hence, the melt flow effect on laser drilling should be reevaluated based on a more realistic model.

A more realistic model should consider vaporization based on the real physics involved. It is known that vaporization occurs at any temperature above the melting point, and that the recoil pressure is highly dependent on the melt surface temperature. However, some previous models assumed a Stefan condition at the melt-vapor interface [7], while some others took the boiling point for the liquid–vapor transition [19]. Solana et al. assumed the recoil pressure to be of the Gaussian form [20]. Li et al. assumed that the liquid–vapor transition takes place over a certain temperature range [21].

How to simulate heat conduction more accurately is also important to better predict the real physics. Heat conduction in solid is a classical problem, but the heat conduction in laser drilling involves a change in boundary conditions, which has led to different approaches by different investigators. Earlier researchers assumed a constant melt layer thickness and a constant melting rate, and consequently developed a steady state heat conduction model [22]. Modest derived a transient heat conduction model by assuming that the phase change from solid to vapor occurs in a single step [23]. By assuming a parabolic temperature profile and applying integration, the partial differential equation was transformed into an ordinary differential equation, which was later applied for an integral solution by Zhang and Faghri [8]. Shen et al. also derived a transient heat conduction model by assuming a temperature profile of exponential function [24]. Ho and Lu