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An investigation of energy loss mechanisms in water-jet assisted underwater laser cutting process using an analytical model

Suvradip Mullick, Yuvraj K. Madhukar, Subhransu Roy, Ashish K. Nath *

Department of Mechanical Engineering, Indian Institute of Technology, Kharagpur, India

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ABSTRACT

The water-jet assisted underwater laser cutting processes has relatively low overall efficiency compared to gas assisted laser cutting process due to high convective loss in water-jet from the hot melt layer and scattering loss of laser radiation by the water vapour formed at the laser–workpiece–water interaction region. However, the individual contribution of different losses and their dependency on process parameters are not fully investigated. Therefore, a lumped parameter analytical model for this cutting process has been formulated considering various laser–material–water interaction phenomena, different loss mechanisms and shear force provided by the water-jet, and has been used to predict various output parameters including the maximum cutting speed, cut front temperature, cut kerf and the loss of laser power through different mechanisms as functions of laser power and water-jet speed. The predictions of cutting speed, kerf-width and cut front temperature were validated with the experimental results. The modeling revealed that the scattering in water vapour is the dominant loss mechanism, causing ~40–50% of laser power loss. This also predicted that the percentage losses are lower for higher laser powers and lower water-jet speeds. In order to minimize the deleterious effect of vapour, dynamics of its formation due to laser heating and its removal by water-jet was experimentally studied. And, the cutting was done with modulated power laser beam of different pulse on- and off-times to determine the pulse on-time sufficiently short to disallow growth of vapour layer, still cutting be effected and the off-time enough long for water-jet to remove the vapour layer from the interaction zone before next pulse arrives. Compared to CW laser beam the modulated laser beam of same average power yielded higher process efficiency.

1. Introduction

The laser cutting in water environment has attracted much attention in recent years because of its many inherent advantages [1]. Lu et al. [2] reported significant enhancements in laser drilling efficiency and improvement in hole quality in underwater drilling of thin sheets of different metals by Q-switched Nd: YAG laser. Underwater laser processing provides higher impact force and stronger shockwave due to the water confinement of laser produced plasma, intense liquid-jet induced impulses due to the bubble collapse, and better cooling. Laser drilling, cutting, micromachining of brittle materials like glass, silicon wafer, silicon carbide, alumina, etc. carried out in water environment also reportedly have higher processing rates, efficient debris removal, better surface morphology and less thermal damages compared to that in air [3–6]. Besides its several advantages, this process has certain issues, like absorption of laser beam in water and scattering of laser light from the processing zone. Recently, Mullick et al. [7] reported water-jet assisted underwater laser cutting of steel sheets, wherein water-jet readily removed the molten material from kerf with enhanced convective heat loss compared to conventional gas-assist laser cutting. It was found that along with convective heat transfer, absorption of laser light in water column, and scattering of laser beam by water vapour formed at laser–workpiece–water interface zone were contributing significant loss of laser power in water-jet assisted underwater laser cutting process. However, parametric dependence of many of the loss mechanisms and their individual contribution were not fully investigated. The power loss due to scattering was assumed to be constant irrespective of the process parameters [7]. A better understanding of different modes of energy loss during the operation is required for determining the optimum process parameters to improve the process efficiency. Since the quantitative estimation of these losses through experiment is difficult, therefore a lumped parameter analytical model has been formulated to study the

* Corresponding author.
E-mail address: aknath@mech.iitkgp.ernet.in (A.K. Nath).

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Nomenclature

A	absorptivity of the laser power on the work-piece surface
C_f	skin friction coefficient
C_{pl}	temperature dependent specific heat of liquid molten work material
C_{ps}	specific heat of the solid work material
d_{sp}	focal spot diameter of laser beam
h_c	convective heat transfer coefficient of water
H_L	absorbed laser power density
j_e	rate of evaporation of work material
K_b	Boltzmann constant
K_l	temperature dependent thermal conductivity of liquid molten work material
K_s	thermal conductivity of solid work material
K_w	thermal conductivity of water
L	total water column height above work-piece surface
L_1	location of the focal point with respect to water surface
L_2	distance between focal point and work-piece surface
L_m	latent heat of melting of work material
L_v	latent heat of vaporization of work material
L_{vm}	molecular latent heat of vaporization of work material
M^2	beam quality parameter
m_a	atomic mass of material vapour
m_v	percentage of material vaporization
P_{av}	average laser power
p_i	initial/atmospheric pressure
p_{in}	laser power supplied by the laser machine
P_L	laser power incident at the work-piece material
Pr	Prandtl number
p_s	saturation vapour pressure
P_s	laser power lost by scattering
P_T	laser power lost by direct transmission of the beam through the cut kerf
q_s	rate of heat conduction to base material
q_w	rate of convective heat transfer from melt layer to water-jet
R	universal gas constant
Re	Reynolds number
S	specific energy, J/mm^3
t	thickness of the work-piece
T_a	atmospheric/room temperature
T_l	melt front temperature
T_m	melting temperature of work material
T_{off}	pulse off-time
T_{on}	pulse on-time
u, v	velocity components along the x and z axes
v_c	cutting speed
v_l	velocity of melt layer
v_m	velocity of melt isotherm
v_w	average water-jet speed
w	average kerf-width of the cut
w_0	beam radius at the focal point
w_s	beam radius at the water surface
w_t	beam radius at the top surface of work-piece
w_z	beam radius at the bottom surface of work-piece
x, z	axes along the surface of the work-piece and along the direction of water flow
α	equivalent absorption coefficient of water at 1.07 μm wavelength
α_L	linear absorption coefficient of water at 1.07 μm wavelength
δ_{df}	thermal diffusion length of work material
δ_l	melt layer thickness
θ	inclination angle of the cut front
λ	wavelength of laser light
μ_l	temperature dependent viscosity of molten material
ρ_l	density of liquid molten work material
ρ_s	density of the solid work material
ρ_w	density of water
τ_c	time required for melt front to reach the bottom surface of the work material
τ_w	shear stress provided by the water-jet

major power loss mechanisms in the process.

There has been extensive research on the modeling of laser material processing including gas assisted laser cutting and drilling in air, thermal modeling of water micro-jet guided laser processing, and investigation on different primary and secondary losses in gas assisted laser processing in air and different underwater laser processing. Yilbas et al. [8] developed a theoretical model of gas assisted laser cutting mechanism to study the interaction between liquid metal and gas jet. The effect of gas-jet on cutting mechanism and formation of liquid layer was analyzed considering the momentum effects only. In that study they considered that the one side of liquid melt layer is being dragged away by a gas boundary layer and on the other side liquid metal is continuously created and fed into the liquid layer. In another study Yilbas and Kar [9] carried out the thermal and efficiency analysis of CO_2 laser cutting process. They estimated an approximate magnitude of heat absorbed during cutting process and the thickness of melt layer, considering the momentum and gas–liquid interface shear stress provided by the assist gas-jet. Li et al. [10] developed a lumped parameter model for the gas assisted laser cutting process. The model took into account the threshold incident laser power for the initiation of cutting process. They considered the conduction loss and neglected the convective and radiative energy losses, and investigated the effect of different process parameters such as laser power, spot size and cutting speed on the cut depth using the model.

Samant and Dahotre [11] developed a hydrodynamic model of laser machining which can predict the required thermal energy and time for machining material up to a particular depth. This model incorporated the multiple reflection of laser beam, effect of vapour pressure for expelling out the molten material, thermal effects of melting, material loss due to evaporation and the effect of surface tension. They also considered the transient effect of laser beam defocusing due to the change in machining depth as a function of expelled material. Different primary losses for inert gas fusion cutting were modeled by Scintilla et al. [12], which took into account the direct transmission of laser beam through kerf and reflection of laser beam from work surface. The results of primary loss in different sheet thicknesses and cutting speeds revealed that the transmission loss is inversely proportional to cutting speed and sheet thickness.

Rao and Nath [13] and Rao et al. [14] studied the dynamic behavior of melt ejection in laser cutting titanium sheet to obtain dross free cuts with minimum heat affected zone (HAZ) using CO_2 laser. They calculated the shear stress exerted by assist gas assuming very large kerf-width compared to the gaseous boundary layer thickness and constant gas density in kerf zone.

Li et al. [15,16] developed a finite difference model for the water-jet guided laser drilling and grooving of silicon, and simulated the thermal field taking into account laser energy input,