ABSTRACT

The growing impact of laser machining on various manufacturing processes has motivated the present work entitled "THERMAL-HYDRAULIC PHENOMENA IN LASER-MATERIAL INTERACTIONS" which pertains to the studies on some important and specific aspects of laser melting, vaporization and cutting. The work is divided into three distinct parts as follows.

(I) Evaporative Removal of Molten Metal From a Rectangular Cavity with Induced Thermocapillary Flow due to Laser Heating on Liquid Surface

(II) Thermal-Hydraulics of Vaporizing Melt Flow in Gas-Assisted Laser Cutting of Metal Sheet

(III) Theoretical Estimation of Maximum Cutting Speed and Kerf in Ablative Laser Cutting of Metal Sheet

The work in part I refers to a pool of molten metal heated by a laser beam incident on its surface and is subjected to an internal circulation due to a thermocapillary flow with a continuous regression of the liquid-vapour interface because of intense evaporation from the melt surface. A theoretical model based on the numerical solution of mass, momentum and energy in both liquid and gas phases has been developed to predict the rate of evaporation from the interface along with the nature of thermocapillary flow and heat transfer within the liquid pool.

The major feature of the present work, as distinct from the earlier works available in the literature, lies in the coupling of gas phase transport equations to those of the liquid phase to determine theoretically the rate of evaporation from the liquid-gas interface. The velocity and temperature in both the liquid and gas phases have been numerically evaluated and finally the rate of regression of the liquid-gas interface has been predicted as a function of pertinent operating parameters.

A single recirculating flow is induced in the molten metal pool due to thermocapillary action. The flow is much faster near the liquid gas interface and at the edge of solid wall near the liquid surface. An increase in either laser power or in the cavity aspect ratio increases the recirculating flow while the laser spot size has almost no influence on the liquid flow field.

The temperature gradient along the liquid gas interface shows a continuous increase in its value from the central axis to the solid edge of the cavity. The liquid surface temperature at any point increases with time and shows a transient response to a steady state temperature when the incident laser heat flux on the liquid surface is balanced by the evaporative and convective heat loss from the surface. However, the increase in the steady state value of maximum surface temperature is more marked with a decrease in spot size as compared to that with an increase in laser power. The cavity aspect ratio has a negligible influence on the temporal variation of liquid surface temperature. Reduction in melt depth due to evaporation is very slow at the beginning and then becomes fast and reaches an almost constant rate when surface temperature distribution reaches its steady state. The reduction in melt depth due to evaporation is faster with either an increase in laser power or a decrease in spot size but remains virtually invariant with the cavity aspect ratio.

The problem in part II is characterized by the flow of molten metal down the inclined cut edge of a metal sheet due to gravity and drag effect of air jet discharged from a nozzle, during laser cutting. A numerical model has been developed to predict the thermal- hydraulic characteristics of flowing melt along the cut edge in consideration of the drag effect of the air jet, evaporation from the liquid gas interface and melting from the solid-liquid interface. The model is based on the numerical solution of the conservation equations of mass momentum and energy in liquid and gas phases. It has been observed that the melt film thickness, under all operating conditions, increases along the cutting edge indicating a lower vaporization rate of molten liquid compared to the melting rate of the material at any section determined by the value of cutting velocity V_c' considered in the present problem.

An increase in Re_{a_i} (the Reynolds number of air at nozzle outlet), or a decrease in V_R (the ratio of air velocity at nozzle outlet to cutting velocity $= V_a'/V_c'$) or a decrease in W (laser power) results in a decrease in the vaporization rate of molten liquid compared to the melting rate of the material and hence, increases the melt film thickness. However, the influence of W on melt film thickness is marginal, while the influence of V_R on it is a profound one.

The liquid-gas interface temperature rises steeply along the direction of melt flow from the leading edge and remains almost constant within a region where the surface is heated by the central portion of the laser beam, and then decreases gradually to a lower value. The significance of vaporization over melting of the the work material, as characterized by a quantity $M_r = 1 - (\dot{M}_v/\dot{M}_m)$, becomes more with an increase in laser power W, a decrease in Re_{a_i} or with an increase in V_R. An energy efficient cutting process will correspond to an optimised situation of operating parameters like laser power, assist gas velocity and the cutting speed so that material removal takes place with negligible vaporization of the liquid phase of the material.

The studies in part III pertains to transience of melt front propagation velocity in relation to the speed of laser beam with different power levels in case of laser cutting of a metal sheet have been studied from a numerical solution of a three dimensional unsteady heat conduction equation within the work piece. The following features have been observed.

The melt front propagation velocity following a rapid transience from its initial value, tends asymptotically to a steady state value which is equal to the velocity of laser beam set for the purpose. For a given material of a given geometry and at a specified initial temperature, the initial velocity of melt front propagation is a function of the laser power, and sets the theoretical limit of maximum cutting speed under this specific situation. The maximum cut width behind the melt front, defined as kerf, reaches a constant value when the melt front or leading cut surface attains its steady state velocity. An increase in laser power or a decrease in laser velocity increases the kerf.