Investigations on Thermodynamic Behaviour of CO_2 Laser Cutting process

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ABSTRACT

In CO_2 laser gas-assisted cutting process, modelling of the interaction mechanism is important. Consequently, the present study treats the complete problem of the interaction of the melting surface with the boundary layer and describes the behaviour of the melting layer. In the analysis, gas - liquid interface parameters are developed and relationships between the parameters influencing the cutting action are identified theoretically. To achieve this, effects of momentum and gas - liquid interface shear stress, due to the assisting gas jet, are considered. The approximate magnitude of the heat absorbed is estimated and melting layer thickness is predicted. An experiment is carried out and the theoretical predictions are compared with the experimental findings. First and second law efficiencies of the cutting process are predicted, which may, then, be used to improve the process. It is found that the assisting jet velocity increases the first and second law efficiencies of the CO_2 laser cutting process.

Keywords: Laser cutting speed, gas jet velocity, first and second law efficiency

I. INTRODUCTION

Medium and high-power industrial CO_2 lasers can be used for cutting, welding, drilling, scribing, marking and many kinds of thermal surface modification. Laser processes are clean, rapid and usually involve low overall heat input to the work piece, so minimizing distortion. Processing forces are minimal and many laser techniques are ideal for industrial applications. If laser light hits a solid target with sufficient power intensity a complex process starts involving first the heating of the target while it is in the solid state, with subsequent melting, vaporization and ionization.

II. LITERATURE REVIEW

It has been shown that this complex process affects the resulting end products. For example drilled holes, cuts, welds, etc.[1]. Many methods have been suggested and tried to improve the use of lasers for machining purposes [2]. However, it has also been shown that laser machining can be improved by controlling the physical parameters involved with the laser/work piece interaction process, such as the plasma absorption coefficient, ambient pressure, plasma electron number density and temperature. Previously, it has been shown that the effect of the surface plasma in laser cutting processes had a very significant effect on the cut quality[1]. Therefore, further studies into the surface plasma properties are essential.

Alternatively, two different cutting techniques have been developed with the introduction of a gas in the cutting section [3]. (1) In laser fusion cutting the material is melted by the radiation energy of the laser and the melt is blown by a gas introduced from a nozzle. In this case shielding gas is required for combustible materials. (2) The material may be eroded by vaporisation, i.e. oxygen is used in the cutting section. In laser oxygen cutting, material is heated to ignition temperature by the focused laser beam. Consequently, a high temperature oxidation, exothermic reaction takes place during the cutting. This reaction provides extra energy in the cutting section. The oxygen provides: (a) increased absorption of incident laser energy by the work piece; (b) considerable additional energy through the exothermic reaction, increasing the cutting process; (c) cleaning of molten metal oxide from the cutting section; and (d) cooling and protection of the focusing lens from liquid and vapour emission.

Considerable research studies were carried out to investigate the laser heating project [6-13].The analysis of acoustic sensing for laser grooving and cutting was carried out by Sheng and Chryssolouris [14].They introduced the process control scheme for groove depth and beam breakthrough regulation for laser cutting process. Surface temperature due to a moving laser cutting beam was formulated by Romer Meijer[15].They presented two types of approximating functions relating the scanning speed to the maximum surface temperature. Three-dimensional conduction model in relation to laser machining process was introduced by Modest[16].He predicted the shape of a developing groove that was formed by ablation of material by a stationary as well as moving laser beam. Temperature field during laser forming of beam was examined by Ji and Wu[17].They employed finite element method when solving this governing equation of heat transfer. They showed that temperature gradient in a depth below the surface increased with increasing of laser power and work piece thickness while it decreased by laser beam scanning velocity. A dual gas jet laser cutting process involving co-axial and off-axial oxygen gas flowing was investigated by Hsu and Molian [18].They showed the effectiveness of the dual gas-jet in achieving the maximum machining rate without deteriorating the cut quality. The turbulent boundary laser approach allowing chemical reactions for CO_2 laser oxygen-assisted cutting process was introduced by Yilbas and Sahin[19].They showed that heat transfer to the liquid metal decreased with increasing work piece thickness. The thermal analysis of laser cutting process was studied by Yilbus [20]. He indicated that the mathematical model employed presented the physical phenomena well, with the limit of characteristic distance, striation frequency and striation width, as predicted, agreeing well with the experimental findings. A numerical study for CO_2 laser cutting process was carried out by Yilbas [21].The melting front velocities at different laser output power and work piece thickness were predicted.

In laser cutting process, the end product quality is the determining factor for the successful machining operation. However, some cutting quality deviations can be attributed to slow process drifts and disturbances. Many reasons can be associated for such drifts. Some of these may include work piece property variations, assisting gas pressure fluctuations, laser output power variation and optical integrity perturbations. Considerable research studies were carried out to assess the end product quality of laser cutting process. Investigation into instabilities in laser cutting was carried out by Simon and Gratzke [22].They investigated that cutting speed less than the speed of the moving molten layer, sideways burning occurred, which in turn resulted in the formation of striation patterns. Scultz and Becker [23] studied the kerf width formation during laser fusion cutting. They introduced a model predicting the self adjusting kerf width. Powell et al[24] investigated laser cut edge quality improvements through pulsing the laser beams. They indicated that the pulsation in the molten layer prior to it being blown down from the kerf could cause periodic striations. Kar et al. [25] introduced scaling law to predict the kerf width during laser gas assisted cutting process. They indicated that thick metal cutting performance could be improved by producing narrow widths. Laser cutting parameters were investigated experimentally by Yilbas [26].He showed that smoothness of kerf surface deteriorate once the cutting speed increased to critical speeds and beyond the limits cutting ceases. The Taguchi method for determining CO_2 laser cut quality was introduced by Yilbas [23].He showed that the end product quality improved at certain combination of the levels of the cutting parameters.

The operating cost of a laser system is high when operated insufficiently, i.e. efficient operation is desirable. Moreover, high material removal rate, high dimensional accuracy, good end product quality and high degree of process repeatability must be achieved to ensure the laser machining operation viable. Consequently, investigation into thermodynamic efficiencies (first and second law efficiencies) and quality assessment of the end product in laser machining operation is essential. In the present study, oxygen assisted CO_2 laser cutting of sheet metal is considered. The kerf width is presented analytically using the scaling laws [20,24] and the parametric study based on a factorial analysis is introduced to access the resulting cut quality.

III.THERMODYNAMIC INVESTIGATION AND MODELLING OF CUTTING PARAMETERS

To perform the calculation of laser cutting parameters (liquid layer thickness and laser-power requirements), the flow field developed at the gas-liquid boundary needs to be considered. Flow equations derived in the previous study are used. Laminar model for the flow conditions is taken into account and the following assumptions are made:

(a) At any time the interface between the liquid layer and solid material is a straight line and is the melting isotherm.

(b) The melting isotherm moves into the solid material with a velocity V_m (melting velocity) and it does so normal to the melting isotherm.

(c) The velocity of the melting isotherm is considered as the cutting speed.

(d) The blowing jet is attached to the molten liquid layer at any instant and throughout the molten layer.

(e) The physical properties of the liquid layer ($\rho_l, K_l, \mu_l, C_{pl}$) and of the solid material ($\rho_s, K_s, \mu_s, C_{ps}$) are constant throughout the liquid layer and the solid material.

(f) The thickness of the liquid molten metal remains constant for a particular gas jet velocity and melting velocity at any instant.

In the light of the above assumptions, the establishment of the liquid layer thickness may be formed through the following steps.

It was shown previously that inverse of the liquid-gas interface shear stress is[1]

$$\frac{1}{\tau_g} = \frac{I_e - h_g}{U_e \, Pr^{2/3} q_s} \qquad (1)$$

where is the gas-liquid interface shear stress and can also be written as

$$\tau_g = \frac{c_f}{2} \rho_e U_e^2 \qquad (2)$$

$$\tau_g = \mu_l \left(\frac{U_l}{\delta_l} \right) \qquad (3)$$

Combining eqns. (1) – (3) results in

$$\delta_l = -\mu_l \left(\frac{U_l}{\delta_l}\right)^2 \frac{I_e - h_g}{Pr^{\frac{2}{3}} q_g \, U_l} \qquad (4)$$

Knowing that[1]

$$I_e - h_g = \frac{q_l}{C_H \, \rho_e \, U_e} \qquad (5)$$

And combining eqns. (4) and (5) yields

$$\delta_l = \mu_l \left(\frac{U_l}{U_e}\right) \frac{1}{\left(\frac{C_f}{2}\right) \rho_e U_l} \qquad (6)$$

Since $q_l = q_g$ and $C_H = \left(\frac{C_f}{2}\right) Pr^{-2/3}$.

It is also shown that[13]

$$\frac{U_l}{U_e} = \frac{5}{2} \frac{C_f \rho_e m_l S}{\rho_l \mu_l} \qquad (7)$$

Where **S** is the Stanton number. Substituting eqn. (7) in to eqn. (6), yields

$$\delta_l = \mu_l \frac{5}{2} \frac{C_f \rho_e m_l}{\rho_l \mu_l S} \frac{1}{\left(\frac{C_f}{2}\right) \rho_e U_l} \qquad (8)$$

Or

$$\delta_l = \frac{5}{2} \frac{m_l S}{\rho_l U_l} \qquad (9)$$

Where $m_l = \rho_l V_m$.

Knowing ρ_l, U_l *and* m_l, the liquid layer thickness can be calculated. To determine the heat transfer rate at the gas-liquid interface, it becomes customary to calculate the temperature rise across the liquid layer. Consider the heat transfer to the solid material. This will be less than that transferred from the hot-gas boundary layer to the liquid metal by an amount equal to that absorbed by the molten layer. If the molten layer does not flow back along the surface, heat absorbed per unit area is at the rate of

$$\frac{1}{2} C_{pl} m_l (T_l - T_m)$$

Where T_l is the melted surface temperature, m_l the melting rate per unit area and T_m the melting temperature. In practice, the melted layer does flow back down stream and absorbs more heat than it would do if it remained in place. This absorption by the melted layer can be approximated as [13]

$$0.65\, C_{pl} m_l (T_l - T_m) \qquad (10)$$

Consequently, the rate of heat transfer to the solid under the material is approximately

$$q_s = q_l - 0.65\, C_{pl} m_l (T_l - T_m) \qquad (11)$$

Or

$$q_l = q_s + 0.65\, C_{pl} m_l (T_l - T_m) = K_l (T_l - T_m)/\delta_l \qquad (12)$$

Rearranging eqn (12) yields

$$T_l - T_m = \frac{q_s}{\left(\frac{K_l}{\delta_l}\right) - 0.65 C_{pl} m_l} \qquad (13)$$

Where

$$q_s = m_l \left[L_m - C_{ps}(T_m - T_0)\right]$$

Knowing q_s, $(T_l - T_m)$ can be determined and, consequently, $q_l$can be calculated. One of the explanation of the above analysis is that if a power intensity ql is applied at the gas-liquid interface, the melting isotherm T_m at the liquid-solid interface will advance into the solid material with a velocity V_m which is the cutting velocity deÞned as the speed at which the isotherm T_m propagates into the solid material.

IV. FIRST AND SECOND LAW ANALYSIS OF CUTTING PROCESS

In laser cutting process, heat input due to laser radiation increases the temperature of the solid metal to liquid temperature, i.e. temperature of the base metal increases from T_0 to T_l . The heat input required for this process is

$$(q)_{req} = m_l \left[\int_{T_s}^{T_m} C_{ps}\, dT + L_m\right] = m_l \left[\, C_{ps}(T_m - T_o) + L_m\right] \qquad (14)$$

Assuming $C_{ps}$is constant,The actual heat input due to laser irradiation is given by eqn(12), which is

$$q_l = m_l \left[C_{ps}\,(T_m - T_0) + L_m\right] + 0.65 C_{pl}(T_l - T_m)$$

Consequently, the first law efficiency becomes

$$_I = \frac{q_{req}}{q_l} = \frac{C_{ps}\,(T_m - T_o) + L_m}{C_{ps}\,(T_m - T_o) + L_m + 0.65 C_{pl}(T_l - T_m)} \qquad (15)$$

Noting that during the heat transfer process, temperature of the base material increases, first, from T_o to T_m, then from T_m to T_l.
The second law efficiency (energy efficiency) includes the heat required and input as well as the temperatures at which the heat exchange take place.[14] Therefore, second law efficiency is a reasonable measure of the quality of heat transfer. Consequently, the energy required for the laser melting process is $EX_{req} = m_l \left[C_{ps}(T_m - T_o) - T_o C_{ps} \ln\left(\frac{T_m}{T_o}\right) + L_m\left(1 - \frac{T_0}{T_m}\right)\right]$ (16)
And the actual exergy input (EX_{in}) is

$$EX_{in} = q_l\left(1 - \frac{T_0}{T_m}\right) \qquad (17)$$

However, the second law efficiency can be defined as

$$_{II} = \frac{EX_{req}}{EX_{in}} \qquad (18)$$

In this case ,it yields

$$_{II} = \frac{C_{ps}(T_m - T_o) - T_o C_{ps} \ln\left(\frac{T_m}{T_o}\right) + L_m(1 - \frac{T_o}{T_m})}{\left[C_{ps}(T_m - T_o) + 0.65\; C_{pl}(T_l - T_m)\right](1 - \frac{T_0}{T_m})} \qquad (19)$$

Consequently, $_I$ *and* $_{II}$can be computing the variables in equation (19).

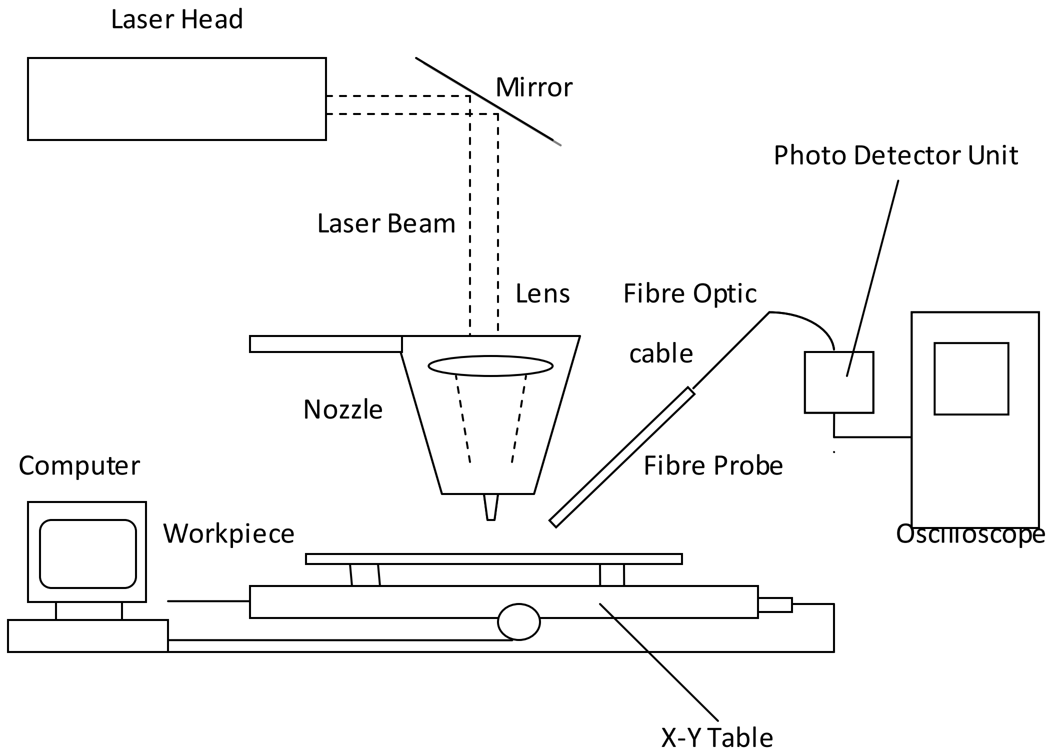


Fig.1. Experimental Setup

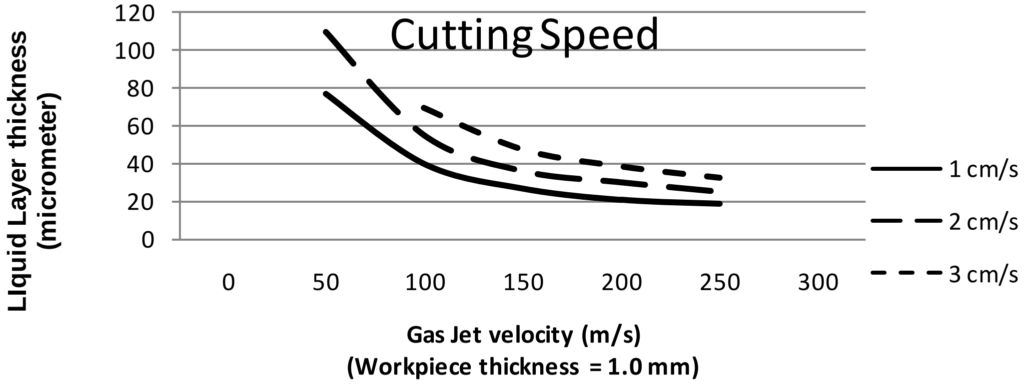
V. EXPERIMENTAL SET UP

The experimental setup is shown in Fig. 1 CO_2 laser delivering 500W output power was employed to cut mild-steel samples of 0.8 to 2 mm thicknesses. 100 mm focal length lens was used to focus the laser beam. Oxygen/argon gas mixture of 5/1 pressure ratio was introduced co-axially with the laser beam through a convergent nozzle of about 0)7 mm exit diameter. To obtain clear boundaries of the resolidified melt zone, cross-sections of the keyhole was etched before taking the photographs. Optical microscope was used to measure the thickness of the resolidified melt zone taking place above the free surface. The experiment was conducted by altering the total oxygen/argon gas mixture pressure from 75 to 172.5 kPa.

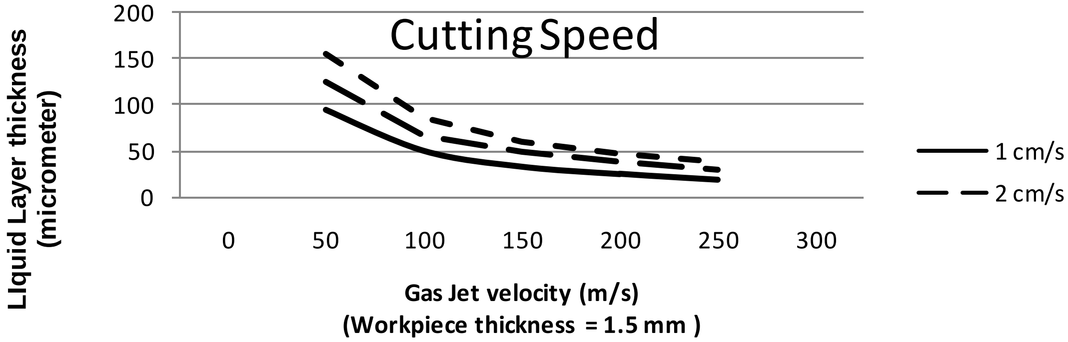
VI. DISCUSSION

For the numerical appreciation of results the following parameters were considered, for the I & II law evaluation of CO_2 laser cutting process. The effects of gas jet velocity, workpiece – thickness and cutting speed have been observed on the performance parameters like liquid layer thickness, required power intensity, I and II Law efficiencies.

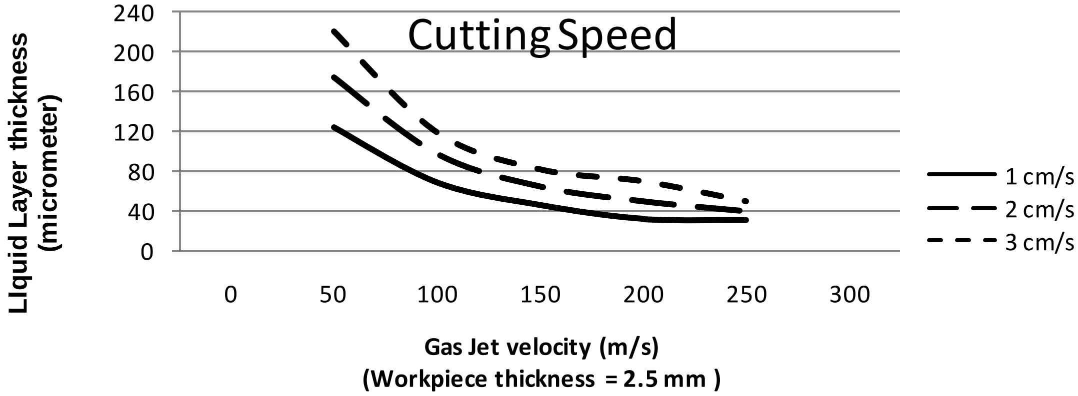
Figure 2 shows variation of the liquid layer thickness with jet velocity for different cutting speeds and work piece thicknesses. It is evident that increasing gas jet velocity decreases the liquid layer thickness, i.e. a large gas jet velocity results in a finite liquid layer. A similar trend may be seen for higher cutting speeds, except that the liquid layer is thicker. In this case, the gas-liquid interface needs to be maintained at a higher temperature, which in turn increases the energy requirement. It is evident that thinning down of the liquid layer occurs with increasing gas jet velocity. This is due to the increase in the interface (gas-liquid) shear stress ,which in turn enhances the blowing rates of the molten metal.



(a)



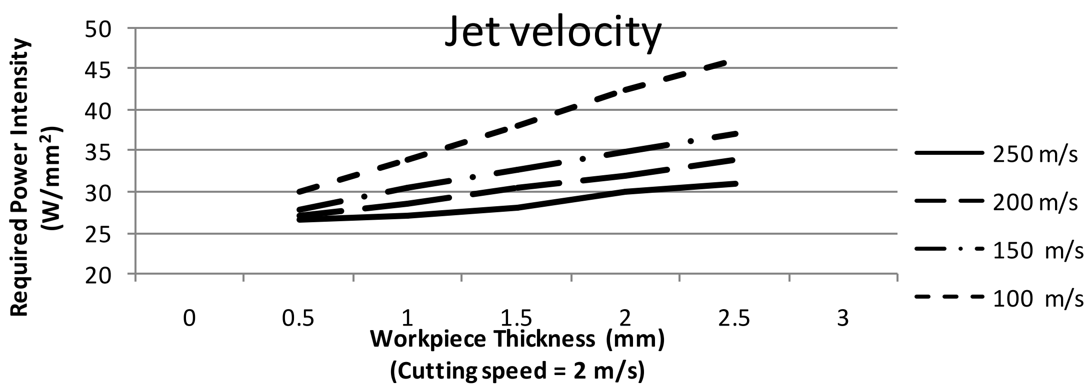
(b)



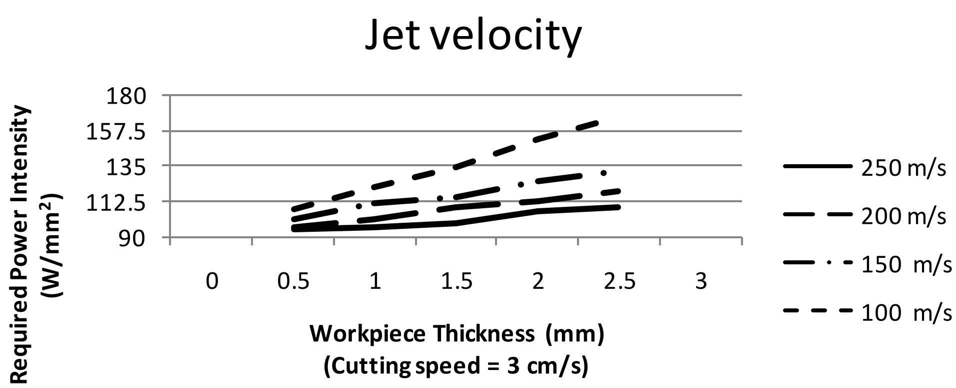
(C)

Fig.2

The variation of the required absorbed power intensity (q_1), distributed over the cut surface at the gas-liquid interface with gas jet velocity is shown in Fig. 3 for different gas jet velocities and cutting speeds. The power intensity requirement (q_1) does not vary considerably with gas jet velocity at low cutting speeds. This is due to that the liquid layer thickness is very small (Fig. 5) and power dissipated in the liquid layer becomes very small. On the other hand, the power intensity requirement at the interface varies significantly with gas jet velocity at great thickness, since the liquid layer thickness and, consequently, interface temperature is high for thick targets. In other words, the interface must be maintained at a higher temperature for thicker materials, in order to maintain the cutting speed, which in turn results in increased absorbed power intensity (q_1) requirement at the gas-liquid interface. It should also be noted that the liquid layer thickness is larger for thicker materials and for lower gas jet velocities. In this case, interface temperatures should be maintained at a higher values which consequently demand increased absorbed power intensity.



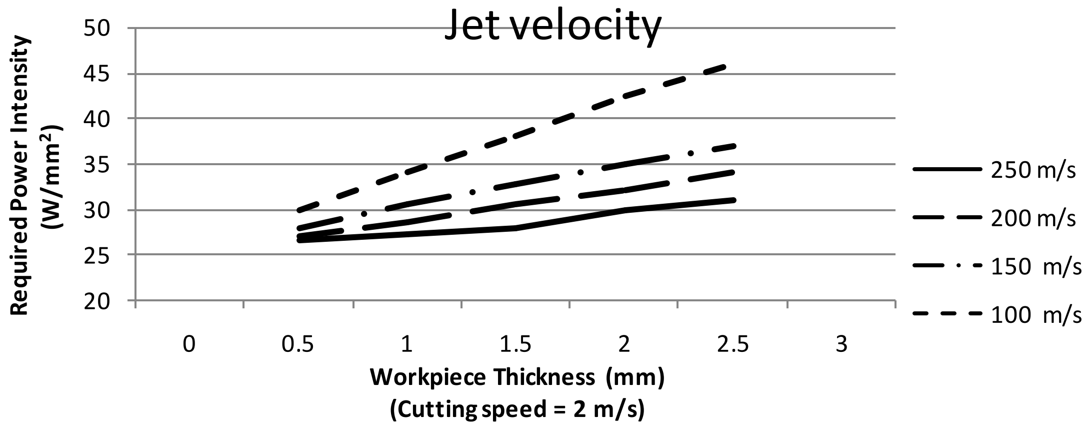
(a)



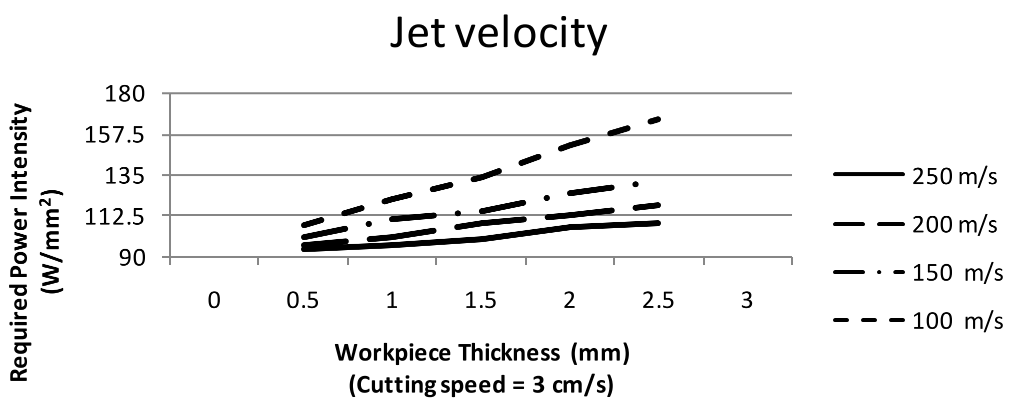
(b)

Fig 3

Figure 4 shows the variation of absorbed power intensity (q_1) with cutting speeds for various gas jet velocities and thickness. Q_1 increases with increasing cutting speeds. The saturation of cutting speed with increasing absorbed power intensity requirement occurs at cutting speed of 8 cm/s. This may be due to that the momentum and hence interface shear stress is insufficient for the liquid-metal removal from the cutting zone at high cutting speeds, and as a result of this mechanism the liquid molten layer becomes thicker with the consequence that a very small fraction of q_1 reaches the solid-liquid interface. A similar argument can be made for the high gas jet velocities with the fact that at high gas jet velocities q_1 is less than that corresponds to low gas jet velocities for the same material thickness and cutting speeds. Figure 5 shows the variation of the liquid layer thickness with gas jet velocity for different work piece thickness, Increasing gas jet velocity decreases the liquid layer thickness. Therefore, the higher the gas jet velocity is there always exists a liquid layer thickness developing on the free surface of the work piece . This justifies the fluid-heating model adopted in this analysis.

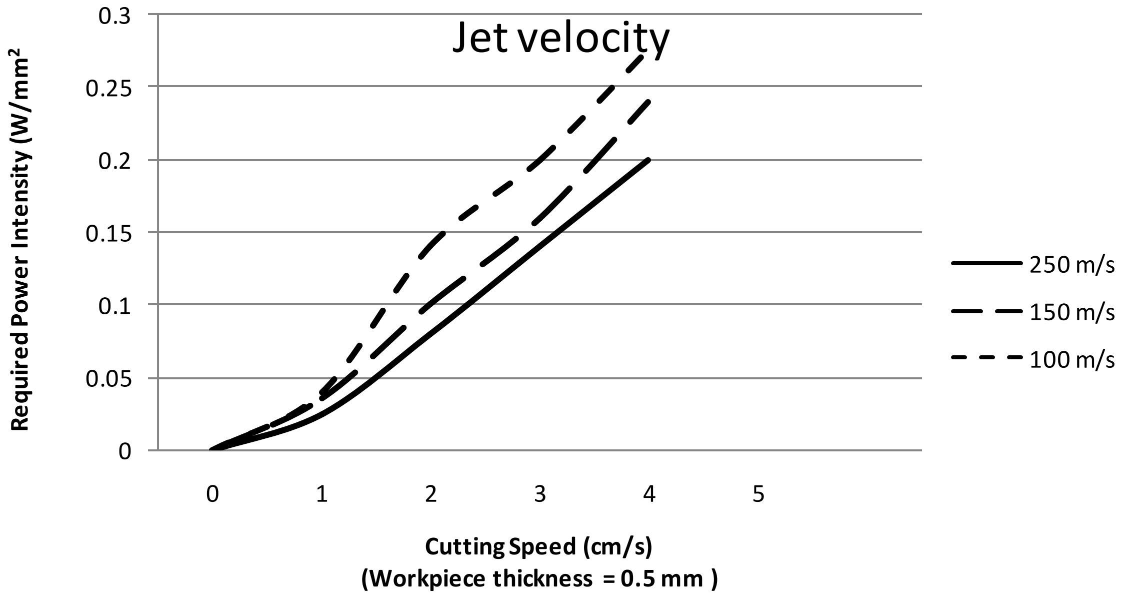

Jet velocity
Required Power Intensity (W/mm²)
50
45
40
35
30
25
20
0
0.5
1
1.5
2
2.5
3
250 m/s
200 m/s
150 m/s
100 m/s
Workpiece Thickness (mm)
(Cutting speed = 2 m/s)

(a)

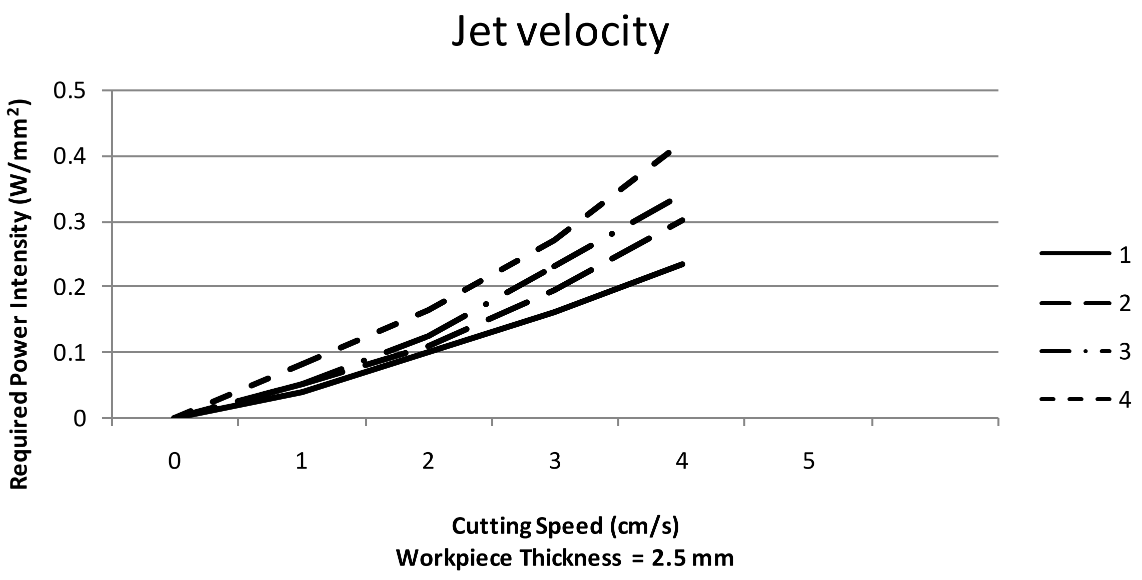

Jet velocity
Required Power Intensity (W/mm²)
180
157.5
135
112.5
90
0
0.5
1
1.5
2
2.5
3
250 m/s
200 m/s
150 m/s
100 m/s
Workpiece Thickness (mm)
(Cutting speed = 3 cm/s)

(b)

Fig.4


Jet velocity
Required Power Intensity (W/mm²
0.3
0.25
0.2
0.15
0.1
0.05
0
0
1
2
3
4
5
250 m/s
150 m/s
100 m/s
Cutting Speed (cm/s)
(Workpiece thickness = 0.5 mm)

(a)



(b)

Fig 5

It is evident that the liquid layer thickness is larger for greater thickness of materials for a corresponding gas jet velocity. This indicates that a higher power is required at the interface for thicker materials as discussed before. The thinning down of the liquid layer thickness with increased gas jet velocity is due to the increase in the gas-liquid interface shear stress, which in turn enhances the blowing rates of the molten metal.

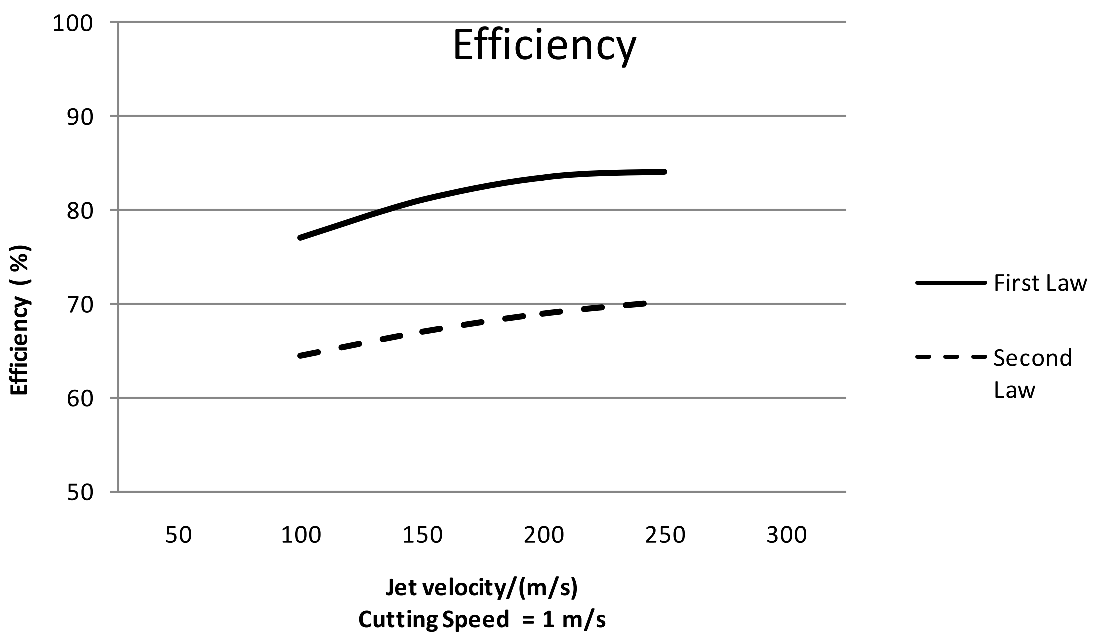


Fig.6

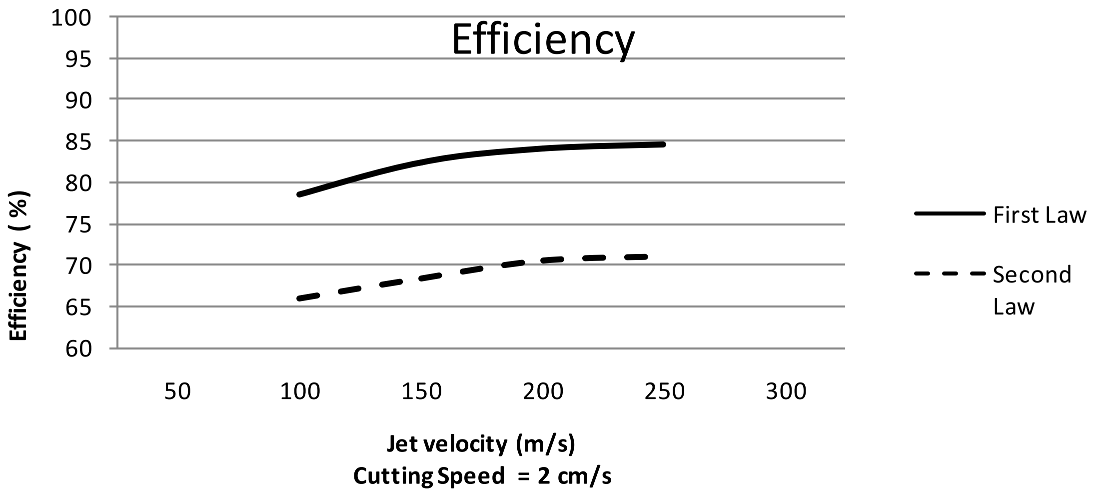


Fig.7

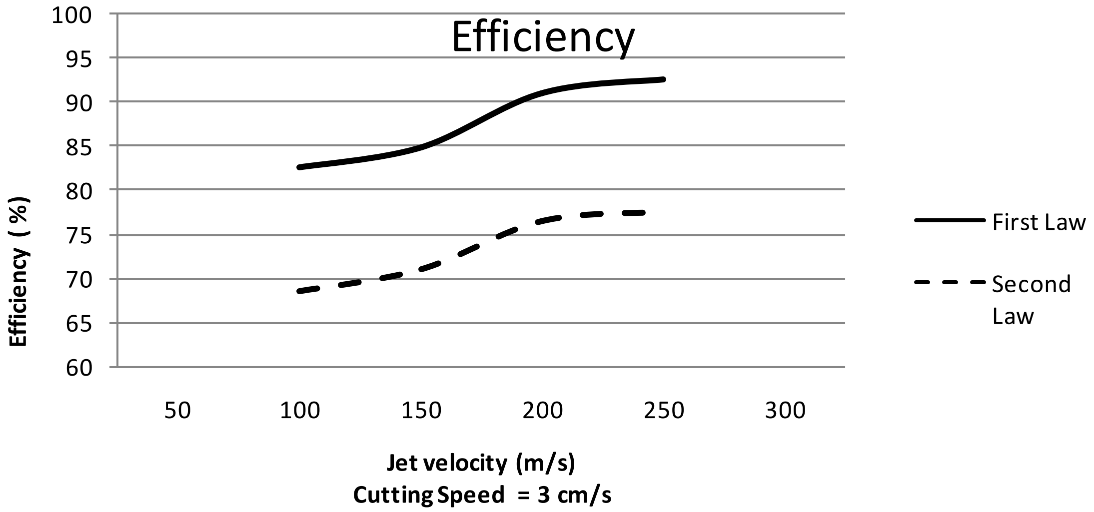


Fig.8

The variation of first and second law efficiencies (energy and exergy efficiencies) with jet velocity is shown in Figs 6-8 for different cutting speeds. It is evident that efficiencies show increasing trend with increasing jet velocities and cutting speeds. The increasing trend of the curves indicates that cutting efficiency, in general, improves at cutting speed of 3 cm/s and jet velocity of 250 m/s. This may again be due to the fact that increase in the jet velocity decreases the liquid layer thickness on the surface, which in turn results more incident laser energy reaching the target. On the other hand, when cutting speed is low, the liquid layer temperature rises and this results unnecessary heat transfer from the liquid layer to surroundings. It should be noted here that the first and second law analyses are valid for the range of data employed in these analyses. Therefore, it is not always the case that at high as jet velocity and high cutting speed, the cutting efficiency is expected to improve, i.e. at gas jet velocities equal or more than speed of sound and for cutting speed more than 8 cm/s, the cutting ceases.

VII. CONCLUSION

The conclusions derived from the present study may be listed as follows:
(1) Increasing gas jet velocity increases the liquid layer thickness. This is due to the increase in gas-liquid interface shear stress.
(2) Power intensity requirement at the gas-liquid interface varies significantly with gas jet velocity at great thickness. In this case, interface temperature must be maintained at higher temperature in order to maintain the cutting speed for thicker materials.
(3) Saturation of cutting speed with increasing absorbed power intensity requirement occurs at cutting speed of 8 cm/s.
(4) Liquid layer thickness measured experimentally is in good agreement with the theoretical predictions providing that little variation occurs in both results due to the experimental error, which was predicted within the range less than 10%, and assumptions made in the analysis.
(5) The first and second law efficiencies of cutting process improve with increasing cutting speed and jet velocity for a given range of data.

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