Laser cutting quality assessment and thermal efficiency analysis

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Abstract

Lasers are widely used in industry as cutting tools due to ultra flexibility of the cutting conditions, obtaining high quality end product, quick set up, non-mechanical contact between the workpiece and the tool, and small size of the heat affected zone. In the present study, laser gas assisted cutting process is examined. Statistical method based on factorial analysis is introduced to identify the influence of cutting parameters on the resulting cut quality. International standards for thermal cutting is employed to identify the measurable variables when assessing the cut quality. Kerf width size is presented using scaling laws. Contribution of high temperature oxidation reaction in cutting due to assisting gas is accommodated in the analysis. First and second law efficiencies for laser cutting process are formulated. An experiment is conducted to assess the cutting quality and validate the Kerf width predictions. It is found that increasing laser beam scanning speed reduces the Kerf width while Kerf width increases with increasing laser output power. The main effects of all the parameters employed have significant influence on the resulting cutting quality. First law efficiency increases with increasing laser scanning speed, which substantiates as the workpiece thickness is doubled.

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Keywords: Laser; Cutting; Assisting gas; Efficiency; Cut quality

1. Introduction

Lasers are used as cutting tools due to high precision of operation and desirable end product quality. In laser cutting process, an assisting gas jet is used. In the case of inert gas assisted processing, assisting gas protects the surface from high temperature oxidation reactions while high temperature exothermic reactions takes place when oxygen is used as assisting gas. In laser gas assisted processing, proper selection of laser and workpiece parameters (cutting parameters) increases the laser cutting efficiency and improves the end product quality.

Considerable research studies were carried out to investigate the laser heating process [1–8]. The analysis of acoustic sensing for laser grooving and cutting was carried out by Sheng and Chryssolouris [9]. They introduced the process control scheme for groove depth and beam breakthrough regulation for laser cutting process. Surface temperature due to a moving laser beam was formulated by Romer and Meijer [10]. 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 [11]. 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 sheet metal was examined by Ji and Wu [12]. They employed finite element method when solving the governing equation of heat transfer. They showed that temperature gradient in a depth below the surface increased with increasing of laser power and workpiece thickness while it decreased by laser beam scanning velocity. A dual gas jet laser cutting process involving co-axial and off-axial oxygen gas flows was investigated by Hsu and Molian [13]. They showed the effectiveness of the dual gas-jet in achieving the maximum machining rate without deteriorating the cut quality. The turbulent boundary layer approach allowing chemical reactions for CO2 laser oxygen-assisted cutting process was introduced by Yilbas and Sahin [14]. They showed that heat transfer to the liquid metal decreased with increasing workpiece thickness. The thermal analysis of laser cutting process was studied by Yilbas [15]. 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 CO2 laser cutting process was carried out by Yilbas [16]. The melting front velocities at different laser output power and workpiece thickness were predicted.

In laser cutting process, the end product quality is the determining factor for the successful machining operation.
Nomenclature

- $a_o = \beta (C_p(T_m - T_o) + L_m + \rho L_k)$
- $A$ energy coupling factor, $<1$
- $A_k$ cross-sectional area of laser cut (m)
- $A_o = \alpha a_o$
- $A_{\beta} = 1/\alpha a_o$\(1 + 2w(T_m - T_o)/2\sqrt{\pi w C / \alpha (1/\alpha a_o)^2}\)
- $B_1$ second law efficiency
- $B_2$ second law efficiency
- $B_3$ second law efficiency
- $C_f$ skin friction coefficient
- $C_{f,\text{in}}$ fraction of evaporation contribution
- $C_{f,\text{out}}$ dimensionless heat transfer coefficient due to chemical reaction
- $C_{f,\text{ex}}$ dimensionless heat transfer coefficient due to diffusion (W/m³ K)
- $C_P$ specific heat (J/kg K)
- $d$ Kerf depth (m)
- $E_m$ rate of energy input (W)
- $E_{\text{req}}$ rate of energy required (W)
- $E_{\text{ex}}$ energy input (W)
- $E_{\text{in}}$ energy required (W)
- $f$ fraction of pressure drop in the Kerf, $<1$
- $F_{p,q}$ variance ratio
- $h_c$ chemical reaction enthalpy (J/kg)
- $k$ thermal conductivity (W/m K)
- $L_b$ latent heat of evaporation (J/kg)
- $L_m$ latent heat of melting (J/kg)
- $M_o$ molecular weight of assisting gas (g/mol)
- $n$ degrees of freedom
- $P_t$ total power input ($P_o + \dot{q}_t$) (W)
- $P_g$ assisting gas pressure (Pa)
- $P_o$ laser output power (W)
- $Pr$ turbulent Prandtl number
- $q_{\dot{L},f}$ heat transfer due to chemical reaction contribution (J)
- $q_{\dot{L},f}$ heat transfer rate due to chemical reaction contribution (W)
- $q_{\dot{L},f,C}$ heat transfer rate per unit area of molten metal (W/m²)
- $q_{\dot{L},f,C,T}$ heat transfer rate across cut width of molten metal (W/m)
- $S_C$ Schmidt number
- $T$ workpiece thickness (m)
- $T_{\text{amb}}$ ambient temperature (room temperature) (K)
- $w_v$ gas velocity at the edge of the boundary layer (m/s)
- $w_e$ melt velocity (m/s)
- $v$ laser beam scanning speed (m/s)
- $w$ laser beam waist diameter at workpiece surface (m)
- $w_k$ Kerf width (m)

Greek symbols

- $\alpha$ thermal diffusivity (m²/s)
- $\beta$ fraction of evaporation contribution, $<1$
- $\eta_1$ first law efficiency
- $\eta_2$ super heating factor in the melt front, $<1$
- $\rho$ density of workpiece material (kg/m³)
- $\rho_g$ density of assisting gas (kg/m³)

Indices

- $g$ gas

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 workpiece property variations, assisting gas pressure fluctuations, laser output power variation and optical integrity perturbations. Moreover, modeling of cutting process gives insight into the physical processes involved, but it leaves obscure the qualitative assessment of the end product quality and efficiency of the process. 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 Gratzeke [17]. They indicated that at cutting speeds less than the speed of the moving molten layer, sideways burning occurred, which in turn resulted in formation of striation patterns. Schultz and Becker [18] studied the Kerf width formation during laser fusion cutting. They introduced a model predicting the self-adjusting Kerf width. Powell et al [19] investigated laser cut edge quality improvements through pulsing the laser beam. 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 [20] introduced scaling laws 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 [21]. 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 CO2 laser cut quality was introduced by Yilbas et al [22]. They showed that cut quality was mainly affected by the oxygen gas pressure and laser beam scanning speed. The cutting quality assessment using a factorial analysis 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 inefficiently, 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 CO2 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 assess the resulting cut quality.

2. Mathematical modeling

2.1. Kerf width formulation

The analysis associated with the influence of assisting gas including cooling and exothermic reaction contribution on the cutting process was examined in the previous study [14]; therefore, the analysis will be described briefly. Assisting gas forms a boundary layer flow over the liquid surface (molten metal surface). The heat transfer from liquid surface to boundary laser flow occurs, since the assisting gas is at room temperature. Since the cooling effect of the assisting gas as well as melting and evaporation taking place at the laser irradiated surface are introduced in the scaling laws, only the exothermic reaction contribution of the assisting gas is introduced. Moreover, high temperature oxidation reaction (exothermic reaction during which metal oxides are formed) at the melt surface provides excess energy to the laser irradiated region during the machining operation. The species formed after the chemical reactions (product of exothermic reactions) contribute to the heat transfer taking place at gas–liquid interface. In this case, heat transfer at the gas–liquid interface due to high temperature oxidation reaction can be described through the ratio of dimensionless heat transfer coefficients due to diffusion (Pr) and chemical reaction (Sc), which was presented as [14]:

\[
\frac{C_{hL}}{C_{hR}} = \frac{1 + B_1(u_1/u_0)^{Pr-1} - 1}{1 + B_1(u_1/u_0)^{Sc-1} - 1}
\]

where

\[
B_1 = \frac{2(\rho u_0)}{\rho_0 u_0 C_f}
\]

and Pr and Sc are turbulent Prandtl and Schmidt numbers, respectively. \(u_0\) is the gas jet velocity at the edge of the boundary layer, \(u_1\) the liquid velocity, and \(C_f\) the skin friction coefficient. The rate of heat transfer \(q_{LJC}\) per unit area (Kerf width \(\times\) Kerf depth) of the molten metal excluding the cooling effect while including chemical reaction contribution of the assisting gas can be written as [14]:

\[
q_{LJC} = \rho u_0 C_{hL} \left[ \frac{C_{hL}}{C_{hR}} - 1 \right] h_c
\]

where \(u_0\) is the gas velocity and \(\rho_0\) the gas density at the edge of the boundary layer, \(h_c\) the chemical reaction enthalpy. It should be noted that \(\Delta h\) being the enthalpy difference of the gas at the gas–liquid interface and edge of the boundary layer, presented in the previous study [14] is cancelled in Eq. (2) due to consideration of exothermic reaction contribution only.

The ratio \(C_{hL}/C_{hR}\) is dependent on \(Pr\) and \(Sc\) and \(B_1\) where \(Pr\) and \(Sc\) are constant. The quantity \(q_{LJC}\) is integrated over each Kerf depth \((d)\) to obtain \(q_{LJCT}\), which is the rate of heat flux over the cut width, i.e.:

\[
q_{LJCT} = \int_0^d q_{LJC} \, dl
\]

The quantity \(q_{LJCT}\) was computed for various Kerf depths as shown in Fig. 1; therefore, the values of \(q_{LJCT}\) computed in the previous study [14] are accommodated in the analysis. Moreover, the quantity \(q_{LJCT}\) can be integrated over the cut width to obtain the rate of chemical energy contribution during the cutting process. Therefore:

\[
q_L = \int_0^d q_{LJCT} \, dl
\]

In the case of a constant laser beam scanning speed, the chemical energy contribution \(q_L\) can be written as:

\[
q_L = \frac{1}{v} q_{LJCT}
\]

The energy balance associated with the cutting process can be simplified through investigating the cutting process by lumped parameter technique [20]. The energy balance exists among the laser energy absorbed per unit depth, conduction and convection heat transfer from the irradiated region, phase changes, and chemical energy contribution. This can be formulated by using the scaling law based on the lumped analysis. The energy balance is formulated and the following relation is deduced [20]:

\[
P = \frac{v u_0 q_l + A_1 \sqrt{\frac{k}{\rho C_p}}}{A_n}
\]

where

\[
P = P_e + q_L
\]

and

\[
A_n = \frac{A}{A_0} \quad \text{and} \quad A_1 = \frac{1}{A_0} \left( \frac{u_0}{w} + 2w(T_e - T_0) \right)
\]

![Fig. 1. Variation of q_LJCT with thickness for different jet velocities. Mild steel workpiece, oxygen is assisting gas, and u_0/w_0 = 0.6.](image-url)
and

\[ a_w = \rho C_p(T_m - T_o) + I_m + \mu L_b \]  

(9)

where \( a_w \) is the Kerf width, \( w \) the laser beam spot size, \( l \) the length of the cut, \( T_m \) the melting temperature of the substrate material, \( T_o \) the ambient room temperature, and \( P_o \) the laser input power. The term \( A_w \) is associated with the energy transport rate to the workpiece material at the surface during the cutting process. \( A \) is the effective energy coupling factor at the substrate material surface. \( \beta \) is the contribution of evaporation of the material, and \( \beta \) is the fraction of evaporation contribution.

\[ \rho = 7880 \text{ kg/m}^3 \]

Density of workpiece

\[ \rho_g = 1.97 \text{ kg/m}^3 \]

Density of assisting gas

where \( \rho \) is the density of the workpiece, \( \rho_g \) the density of the assisting gas, and \( \mu \) the superheating factor in the melted zone.

Eq. (10) is used to determine the Kerf width, provided that Eqs. (6), (8) and (9) are employed to obtain \( A, A_w, \) and \( \beta \). Mathemtica Software Package is introduced during the simulations. Table 1 gives the properties of the substrate material and the assisting gas.

2.2. Thermal efficiency of cutting process

Thermal efficiency of laser cutting process can be grouped into first and second law efficiencies. The ratio of energy required to remove substrate material in the Kerf to laser energy input for the cutting process defines the first law efficiency of the cutting process, i.e. the first law efficiency is based on the first law of thermodynamics [25].

\[
\eta = \frac{\dot{E}_{req}}{\dot{E}_{in}}
\]

(16)

In successful laser cutting process, the rate of mass removed from the Kerf during the cutting process can be written as:

\[
\lim_{\Delta t \to 0} \frac{\Delta m}{\Delta t} = \frac{d}{dt}(\rho \Phi) = \rho \Phi w k_d
\]

(11)

where \( \Phi \) is the volume, \( v \) the laser beam scanning velocity and \( A_w \) the cross-sectional area of the cut, which is \( \alpha_k = w_k d \).

The rate of energy required \( (\dot{E}_{req}) \) to melt the substrate material during the cutting process can be written as:

\[
\dot{E}_{req} = \frac{dE}{dt} = \frac{d}{dt}\int_{T_o}^{T_m} \rho \Phi C_p \Phi dT + \frac{d}{dt}(\rho \Phi(L_m + \beta L_b))
\]

(12)

\[ w_k = \frac{1}{l} \left[ \frac{2.51 (T_m - T_o)}{k(T_m - T_o)} P_o \sqrt{\frac{\rho}{T_o}} \right] \]

(10)

For constant properties, Eq. (12) reduces to

\[
\dot{E}_{req} = \rho \Phi w_k T \int_{T_o}^{T_m} C_p \Phi dT + \rho \Phi(L_m + \beta L_b)
\]

(13)

\[
\dot{E}_{req} = \rho \Phi w_k T \int_{T_o}^{T_m} C_p \Phi dT + (L_m + \beta L_b)
\]

(14)

The rate of energy input \( (\dot{E}_{in}) \) during the laser cutting process including the chemical reaction contribution is

\[
\dot{E}_{in} = \frac{dE_{req}}{dt} = P
\]

(15)

where \( P \) includes the laser output power and the rate of chemical reaction contribution to the cutting process.

Therefore, the first law efficiency can be written as:

\[
\eta = \frac{\dot{E}_{req}}{\dot{E}_{in}}
\]

In the case of second law efficiency, the exergy required for mass removal from the Kerf and exergy input for the cutting process should be considered [26]. In this case, the exergy required can be determined after considering the entropy generation during the heating and phase change (melting and partially evaporation) of the substrate material while exergy input can be determined from the Carnot efficiency [26]. Therefore, the second law efficiency is a reasonable measure of the quality of heat transfer. It should be noted that the laser beam is generated from a source at a temperature almost equals to the ambient room temperature \( (T_o) \), consequently, laser thermal efficiency associated with the lasing system is not considered in the analysis. After considering constant thermal properties, the rate of exergy required for the mass

Table 1

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling temperature</td>
<td>3133</td>
<td>K</td>
</tr>
<tr>
<td>Density of assisting gas</td>
<td>1.97</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Density of workpiece</td>
<td>7480</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Fraction of evaporation contribution (( \beta ))</td>
<td>0.1</td>
<td>–</td>
</tr>
<tr>
<td>Fraction of pressure drop (( f ))</td>
<td>0.1</td>
<td>–</td>
</tr>
<tr>
<td>Energy coupling factor (( A ))</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Superheating factor in the melt front (( \alpha_w ))</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td>Latent heat of melting</td>
<td>2.72 x 10⁵</td>
<td>J/kg</td>
</tr>
<tr>
<td>Latent heat of boiling</td>
<td>6.3 x 10⁵</td>
<td>J/kg</td>
</tr>
<tr>
<td>Melting temperature</td>
<td>1809</td>
<td>K</td>
</tr>
<tr>
<td>Molecular diameter of oxygen</td>
<td>6</td>
<td>Å</td>
</tr>
<tr>
<td>Specific heat capacity of workpiece</td>
<td>440</td>
<td>J/kg K</td>
</tr>
<tr>
<td>Superheating factor</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td>Thermal conductivity of workpiece</td>
<td>80.3</td>
<td>W/m K</td>
</tr>
<tr>
<td>Thermal diffusivity of workpiece</td>
<td>2.21 x 10⁻⁵</td>
<td>m²/s</td>
</tr>
</tbody>
</table>
removal from the Kerf can be written as:

\[
\dot{E}_{\text{ex,req}} = \frac{d}{{df}} \left[ C_p(T_m - T_i) - T_e C_p \ln \left( \frac{T_m}{T_i} \right) \right] \\
+ J_m \left( 1 - \frac{T_m}{T_i} \right) + H_a \left( 1 - \frac{T_m}{T_e} \right)
\]  

(17)

Moreover, the exergy input for the cutting process can be written as:

\[
\dot{E}_{\text{ex,in}} = \dot{E}_{\text{in}} \left( 1 - \frac{T_o}{T_m} \right)
\]  

(18)

Therefore, the second law efficiency can be written as:

\[
\eta_{\text{II}} = \frac{\dot{E}_{\text{ex,req}}}{\dot{E}_{\text{ex,in}}}
\]  

(19)

Eq. (19) is used to compute the second law efficiency.

3. Experimental

3.1. Experimental apparatus

A schematic view of experimental apparatus is shown in Fig. 2. A CO₂ laser delivering output power of 1600 W was used and ZnSe lens was employed to focus the laser beam. Oxygen as assisting gas was introduced co-axially with the laser beam through a conical nozzle. Mild steel workpiece is used in the experiment. The laser power intensity, scanning speed of the laser beam, oxygen gas pressure, and workpiece thickness were varied according to Table 2 during the tests.

Width of the cut, out of flatness of the cut edges and waviness of the cut surface (variation patterns) were measured using a reading microscope while microphotography of cut surfaces was carried out using SEM.

Table 2  Laser cutting parameters and their levels for factorial analysis

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser power, ( P_o ) (W)</td>
<td>750</td>
<td>1000</td>
<td>1250</td>
<td>1500</td>
</tr>
<tr>
<td>Assisting gas pressure, ( P_g ) (kPa)</td>
<td>125</td>
<td>175</td>
<td>225</td>
<td>275</td>
</tr>
<tr>
<td>Workpiece thickness, ( T ) (mm)</td>
<td>0.75</td>
<td>1.00</td>
<td>1.50</td>
<td>2.00</td>
</tr>
<tr>
<td>Laser beam scanning velocity, ( v ) (m/s)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

3.2. Factorial analysis and cut quality assessment

To obtain the effects of laser cutting parameters on the end product quality, a statistical method employing factorial analysis is employed. The cut quality is assessed based on the international standard for thermal cutting (DIN 2310).

3.2.1. Factorial analysis

Two dependent variables namely, waviness and out of flatness of the cut surfaces are considered when assessing the cut quality. To analyze the effect of laser cutting parameters on the dependent variables, the experiment is designed such a way that the influence of each parameter could be examined individually as well as their interactions. This requires a complete factorial design of the experiment in which selected parameters are varied at selected levels. The laser cutting parameters are laser output power, laser beam scanning speed, assisting gas pressure, and thickness of the workpiece.

The mathematical arrangements of factorial design are given in [27]; therefore, it will be briefly presented.

The mathematical model for the present experiment can be written as:

\[
\chi_{ijkl} = \mu + P_{o1} + P_{o2} + T + V + (P_{o1} V)_{id} + (P_{o2} T)_{jk} \\
+ (P_{o2} V)_{id} + (P_{o2} T)_{jk} + (P_{o2} TV)_{id} \\
+ (P_{o2} TV)_{id} + (P_{o2} TV)_{jk} + \epsilon
\]
measured with a reading microscope. In relation to factorial out of flatness. Size of waviness and out of flatness were reduce.Fig. 3 shows schematic view of the waviness and i.e. the cut quality improves as waviness and out of flatness as measurable (dependent) variables defining the cut quality, waviness and out of flatness of the cut edges are considered standards for thermal cutting (DIN 2310). In this case, the cut quality evaluation is carried out in accordance with the block defined in Table 2.

3.3. Cut quality evaluation

The cut quality is evaluated on the bases of international standards for thermal cutting (DIN 2310). In this case, the waviness and out of flatness of the cut edges are considered as measurable (dependent) variables defining the cut quality, i.e. the cut quality improves as waviness and out of flatness reduce. Fig. 3 shows schematic view of the waviness and out of flatness. Size of waviness and out of flatness were measured with a reading microscope. In relation to factorial analysis, a marking scheme is adopted. In this case, marks are assigned to waviness and out of flatness depending on their measured size. After several microscopy readings, it is observed that the mean value of waviness lies within 45 μm while it is 30 μm for out of flatness. Consequently, the following marking scheme is introduced:

For the waviness:
- 0 < waviness < 30 μm ⇒ mark of 3 is assigned,
- 30 μm ≤ waviness ≤ 60 μm ⇒ mark of 2 is assigned,
- Waviness > 60 μm ⇒ mark of 1 is assigned

For the out of flatness:
- 0 < out of flatness < 20 μm ⇒ mark of 3 is assigned,
- 20 μm ≤ out of flatness ≤ 40 μm ⇒ mark of 2 is assigned,
- Out of flatness > 40 μm ⇒ mark of 1 is assigned

4. Results and discussions

Laser oxygen assisted cutting of mild steel workpiece is considered. Kerf width size is presented using scaling laws and its variation with laser output power and laser beam scanning speed is computed. Thermal efficiencies of the cutting process are formulated. Statistical model based on factorial analysis is introduced to determine the affecting parameters on the resulting cut quality. An experiment is carried out to verify Kerf width predicted and to determine the significance levels of affecting parameters and their interactions. Cut edge waviness and out of flatness are considered as dependent variables (measurable variables) while laser output power, assisting gas pressure, workpiece thickness and laser beam scanning speed are selected as independent parameters.

Fig. 4 shows Kerf width predicted from the scaling laws and obtained from the experiment with laser beam scanning speed as laser output power is variable. Kerf width reduces with increasing cutting speed, which signifies particularly at
high laser output power levels. This argument is also true for both workpiece thicknesses (1 and 2 mm). This situation can also be seen from Fig. 5, in which Kerf width with laser output power is shown. In this case, high power intensity enhances the material removal rate from the Kerf. Consequently, Kerf width size increases at high laser output power levels. Moreover, lowering laser beam scanning speed while keeping the laser output power same result in high material removal rate from the Kerf. The influence of workpiece thickness on the Kerf width is not significant; in which case, Kerf width increases slightly with increasing thickness. When comparing the experimental results with the predictions, both results agree well at low scanning speeds. However, as scanning speed increases, some small discrepancies between the results are observed. This occurs because of: (i) coupling effect of incident beam and the melt layer, which improves as scanning speed increases [14], and (ii) the contribution of exothermic reaction to laser cutting process improves with increasing scanning speed [14]. It should be noted that increase in scanning speed does not alter considerably the chemical reaction contribution to total power requirement for cutting is substantial for high gas jet velocities.

Table 3 gives the $F$-test results of the affecting parameters. The influence of laser output power ($P_o$) on waviness and out of flatness is most significant. This indicates that changing of laser power level for given cutting parameters influences the cut quality significantly. In the case of gas reaction contribution to total power requirement for cutting is substantial for high gas jet velocities.

Table 3

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Waviness</th>
<th>Out of flatness</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_o$</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Main effects $T$</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>First order interactions $P_o \times P_g$</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>First order interactions $P_o \times T$</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>First order interactions $P_o \times v$</td>
<td>0.90</td>
<td>&gt;0.90</td>
</tr>
<tr>
<td>Second order interactions $P_o \times P_g \times T$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Second order interactions $P_o \times P_g \times v$</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Second order interactions $P_o \times T \times v$</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
pressure \((P_g)\), the effect is found to be very significant. This shows that the variation in assisting gas pressure does not influence equally the measurable variables when the laser output power varies. The same argument is true for the main effects of the workpiece thickness \((T)\), provided that the influence of thickness on waviness is not as considerable as its effect on out of flatness. The main effect of laser beam scanning velocity is most significant for waviness and out of flatness. Consequently, it is expected that varying laser beam scanning speed influences the cutting quality significantly.

In the case of first order interactions, laser output power and assisting gas pressure, laser output power and workpiece thickness, workpiece thickness and laser beam scanning velocity have very significant effect on the waviness and out of flatness. This prevails that variation in both interacting parameters influences the waviness and out of flatness. Moreover, the effect due to interaction of laser out put power and scanning speed on the waviness is found to be most significant. Therefore, variation in laser output power intensity and scanning speed influences significantly waviness and out of flatness. In the case of second order interactions, only interaction of laser output power intensity-thickness-scanning speed influences waviness and out of flatness significantly, i.e. coupling effect of these parameters on the waviness and out of flatness is significant. Consequently, the cutting condition for increasing laser output power, reducing laser beam scanning speed and workpiece thickness results in side-ways burning, increased Kerf width, out of flatness and waviness. The increased waviness can also be seen from Fig. 6, in which SEM micrographs of cut surfaces are shown. Alternatively, the cutting condition for increasing laser output power, laser beam scanning speed, and workpiece thickness results in improved cutting quality (Fig. 6). Fig. 6 shows the SEM micrographs of laser cut edges and cross-sections.

Fig. 7 shows first law efficiency of the cutting process with scanning speed as laser output power is variable. First law efficiency improves considerably as laser beam scanning speed increases. This occurs because of the improved material removal rate from the Kerf. Consequently, rate of laser output power utilized to remove the molten material from the Kerf increases. Moreover, variation in efficiency with laser beam scanning speed is not linear, i.e. efficiency rises sharper at low scanning speeds than that corresponding to high scanning speeds. This is because of the Kerf width variation,
which decreases sharply as scanning speed increases (Fig. 4).

The influence of workpiece thickness on the efficiency is considerable. In this case, efficiency almost doubles with doubling the thickness. This is due to the amount of material removed from the Kerf, i.e. although Kerf width increases slightly with increasing thickness (Fig. 4), increasing depth (thickness) increases significantly the amount of material removed from the Kerf. It should be noted that change in Kerf width with laser output power is low (Fig. 5), but increasing laser output power reduces the efficiency, i.e. more laser output power is available than it is needed for the cutting process.

Fig. 8 shows second law efficiency with laser beam scanning speed as laser output power is variable. The behavior of efficiency curves is similar to those shown in Fig. 7, provided that the magnitude of second law efficiency is lower than that corresponding to first law efficiency. This is because of the availability of the energy required for the material removal from the Kerf is low due to entropy generation during the cutting process. Moreover, availability of the laser output energy, which is energy input for the cutting process, is high, i.e. it is reduced only by an amount \((T_o/T_m)P\), where \(T_o\) is the ambient temperature, \(T_m\) is the melting temperature of the substrate material, and \(P_o\) is the laser output power. Consequently, the efficiency of the Carnot engine operating between \(T_m\) and \(T_o\) sources is considerably high.

5. Conclusions

Laser gas assisted cutting process is investigated. Laser cutting efficiencies including first and second law efficiency is formulated. Kerf width is presented using scaling laws and the contribution of high temperature oxidation reactions due to assisting gas is accommodated in the analysis. Statistical model based on factorial analysis is carried out to identify the effects of laser cutting parameters on waviness and out of flatness of the resulting cut edges. It is found that cutting quality improves as laser beam scanning speed and laser output power increase mutually. In this case, first and second law efficiencies of the cutting process improve, provided that efficiency reduce slightly as laser output power increases. The specific conclusions derived from the present study are listed as follows:

1. Kerf width reduces with increasing laser beam scanning speed. Increasing laser output power increases Kerf...
width, which is more pronounced at low scanning speeds. Kerf width predicted agreed well with the experimental results.

2. The main effects of all the parameters have significant influence on the resulting waviness and out of flatness. The effect of first order interactions between laser output power and laser beam scanning speed, laser output power and assisting gas pressure as well as laser output power and thickness are found to be significant. This indicates that although laser output power influences the resulting waviness and out of flatness, its interaction with other parameters also influence waviness and out of flatness. It is observed from SEM micrographs that the cut quality improves as laser beam scanning velocity increases, provided that beyond the limit cutting ceases.

3. First law efficiency of the cutting process improves as laser beam scanning velocity increases. In this case, the rate of energy utilized for mass removal from the Kerf increases. Second law efficiency attains lower values as compared to first law efficiency. This is because of the exergy required for mass removal from the Kerf reduces due to entropy generation during the cutting process.

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