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Laser cutting of steel sheets: Influence of workpiece thickness and beam waist position on kerf size and stria formation

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Abstract

CO_2 laser cutting of steel sheets is considered and influence of beam waist position relative to the workpiece surface and the workpiece thickness on the striation formation is examined. The kerf width is modeled using a lump parameter analysis. The measurements are composed with the experimental findings. SEM and optical microscopy are conducted to examine the cutting surfaces. It is found that beam waist position has significant effect on the kerf size and as the workpiece thickness reduces, the relative location of beam waist position varies for the minimum kerf width. The microcracks are found in the resolidified material at the cutting surface, which is due to non-uniform and rapid cooling of the resolidified material at the surface.

Keywords: Laser; Cutting; Beam waist; Stria

1. Introduction

Laser cutting is one of the important applications of laser machining process. In laser gas assisted cutting operation, assisting gas can be reactive or inert depending on the process requirements. In metal gas assisting cutting process, in general, oxygen (reactive gas) is used while argon or helium (inert gasses) is used for wood and plastic cutting. Use of oxygen provides exothermic reaction in the cutting section enhancing the energy available for the cutting process. On the other hand, argon or helium prevents high temperature exothermic reactions and avoids the side ways burnings and excessive mass removal from the cutting kerf. Moreover, regulation of gas pressure and proper selection of nozzle are necessary for controlled cutting process.

In laser cutting, the end product quality is that matters. Due to oscillation in laser output power, assisting gas mass flow rate, material impurities and workpiece scanning speed result in instabilities associated with molten layer in kerf. This, in turn, causes striation formation and out of flatness at the cutting edges. The striation can be characterized geometrically by dross height and stria frequency [1]. The pulsation of laser output power at certain frequencies may reduce the dross height of stria. However, the combination of parameters reducing the dross height has not been established yet. Consequently, investigation into stria characteristics is necessary for improved laser cutting process.

Considerable research studies were carried out to examine laser cutting process. The influence of surface plasma on laser cutting was studied earlier [2–7] and penetration time during laser cutting process was examined by Yilbas et al. [8]. The quality improvements for laser machining operation were considered by Pietro et al. [9]. They indicated that the process manipulation could lead to significant quality improvements. Laser cutting of metallic coated steel sheets was carried out by Wang [10]. He employed a statistical analysis when optimizing the laser cutting process. Laser cutting of non-metallic materials was examined by Zhou and Mahdavian [11]. They introduced two correction parameters to improve the mathematical model. Laser cutting of fibre reinforced plastic composite materials was considered by Cenna [12]. He compared the predictions with experimental results and indicated that they were in good agreement. The parameters affecting the laser cutting process were investigated by Yilbas [13]. He developed a method for pattern classification using an artificial neural network and identified the striation patterns successfully. Laser machining operation was investigated by Meijer [14]. He indicated that the trends in miniaturization in laser machining were expected to continue due to short and

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Nomenclature

A	energy coupling factor, <1
C_p	specific heat at constant pressure (J/(kg K))
d	kerf depth (m)
f	fraction of pressure drop in the kerf, <1
k	thermal conductivity (W/mK)
L_b	laten heat of evaporation (J/kg)
L_m	laten heat of melting (J/kg)
M_w	molecular weight of assisting gas (g/mol)
P	power input in the workpiece (W)
P_0	power input at the workpiece surface (W)
T_m	melting temperature (K)
T_0	ambient temperature (room temperature) (K)
v	laser beam scanning speed (m/s)
w	laser beam waist diameter at workpiece surface (m)
w_k	kerf width (m)
w_0	beam waist diameter at surface when focus setting is nominal (m)
α	thermal diffusivity (m^2/s)
β	fraction of evaporation contribution, <1
σ	the molecular diameter (Å)
η_u	super heating factor in the melt front, <1
ρ	density of workpiece material (kg/m^3)
ρ_g	density of assisting gas (kg/m^3)

ultrashort laser machining techniques. The prediction of melt geometry in laser cutting was considered by Tani et al. [15]. They indicated that the model developed gave reasonably accurate results with the experimental findings. Quantitative evaluation of Nd:YAG laser drilling of mullite-alumina was carried out by Quintero et al. [16]. They performed the analysis by means of analytical image processing. Laser cutting of 4130 steel was studied by Rajaram et al. [17]. They indicated that the low feed rates gave good surface roughness and low striation frequency at the cutting edges.

In laser cutting process, many factors affecting the end product quality. Some of these factors include the focus setting of focusing lens and the workpiece thickness. This is due to that focus setting modifies the power distribution across the focused spot while thickness alters the energy required for full-depth penetration cutting. In the present study laser cutting of steel sheets at different focus setting and workpiece thicknesses are considered. The laser cut surfaces are examined using optical and scanning electron microscopy. The different kerf sizes and striation patterns are identified.

2. Experimental

The CO_2 laser (LC-αIII-Amada) delivering nominal output power of 2 kW at pulse mode with different frequencies is used to irradiate the workpiece surface. Oxygen emerging from a conical nozzle and co-axially with the laser beam is used. One hundred and twenty seven millimeters focal lens are utilized. The cutting conditions are given in Table 1. The workpiece accommodated is hot rolled and pickled HSLA-Steel with its elemental composition is given in Table 2. The workpiece thickness is varied at two levels while focus setting is changed at forty levels. SEM (Jeol JSM6360LV) is used for micrographs of the cutting section while optical microscope is accommodated for striation analysis.

Table 1
Cutting conditions

Feed rate (mm/min)	300
Power (W)	1500
Frequency (Hz)	100
Nozzle gap (mm)	1.5
Nozzle diameter (mm)	1.5
Duty (%)	25
O_2 pressure (kPa)	100

2.1. Kerf width formulations

The energy balance for the cutting process can be simplified by using the lumped parameter technique [18]. Consequently, following relation can be produced after considering the energy balance, i.e. [18]:

$$\frac{P}{d} = \frac{vw_k + A_3\sqrt{vw_k}}{A_0} \tag{1}$$

where

$$A_0 = \frac{A}{a_0} \quad \text{and} \quad A_3 = \frac{1}{a_0}\frac{(w_k + 2w_k(T_m - T_0))}{2\sqrt{\alpha w w_k}} \tag{2}$$

and

$$a_0 = \rho(C_p(T_m - T_0) + L_m + \beta L_b) \tag{3}$$

where w_k 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_0 the ambient room temperature and P is the laser input power. The term A_0 represents 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. A_3 is associated with the conduction energy loss in the solid phase of the substrate material, and, β is the contribution of evaporation of the surface.

Applying scaling law for the laser cutting process, the kerf width resulted due to a circular beam waist size of w can be written as [18]:

$$w_k = \frac{1}{v}\left[\frac{2.51\sqrt{\frac{\alpha}{w}\frac{(2A\eta_u)}{k(T_m - T_0)}}\,P\sqrt{v}}{1 + 3.08\times10^7\left(\frac{A_0}{A_3\sqrt{f}}\right)\left(\frac{\rho\rho_g\sigma^2\alpha}{M_w P_g f\sqrt{w}}\right)P\sqrt{v}}\right] \tag{4}$$

where f is the fraction of pressure drop in the kerf, σ the molecular diameter (Å, Angstrom unit), M_w the molecular weight (g/mol unit) of the assisting gas, P_g and ρ_g the pressure and density of the assisting gas and η_u is the superheating factor in the melted zone.

Table 2
Elemental composition of the HSLA-Steel used in the experiment (wt%)

C	0.12
Si	0.10
Mn	1.20
P	0.02
S	0.01
Al	0.02
Nb	0.07
Ti	0.05
V	0.10
Fe	Balance