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Role of Combustion Energy in Laser Cutting of Austenitic Stainless Steel

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Abstract: Cutting of austenitic stainless steel of 0.5mm and 2mm thickness with CO_2 laser has been carried out using oxygen, nitrogen and compressed air as assist gases. It has been observed that when oxygen is used as assist gas, the contribution of combustion energy was found to be 60 to 80 % more as compared to the other two types of assist gases. The cutting speed for 0.5 mm sheet was about 11 times where as for 2 mm stainless steel it was around 16 times. The role of combustion energy were theoretically calculated and compared with experimental results and found to be in good agreement.

Introduction

Laser cutting has gained increasing interest in the metal forming industry and is well suited for high volume automated manufacturing owing to the high processing speed, low material wastage, precision of operation and high quality of end product [1]. In laser cutting process, the basic parameters are cutting speed, kerf width, laser power, chemistry of assist gas, nozzle exit pressure, nozzle design, workpiece thickness and surface quality [2].

The assist gas used in laser cutting plays two roles, i.e., (a) to shield the surface from oxidation and (b) to generate the exothermic reaction to enhance the cutting process. The former finds application in cutting of non-metallic materials such as plastic and wood and the latter is employed in mainly sheet metal cutting [1]. In oxygen assist laser cutting, the gas jet plays two roles; one is to generate additional thermal energy due to exothermic reaction during formation of FeO and other oxides. The second role is to supply the shear force to the gas / liquid boundary to eject the molten metal formed during the cutting process.

A number of theoretical and experimental studies [3-10] have been carried out to examine the laser gas assisted cutting process. Many authors have attempted to determine the contribution of combustion energy during the cutting process. The authors [11-13] have reported the contribution of combustion energy ranging from 40% to 70%. Many researchers [14-17] have studied the effect of gas pressure on the cut quality. Kamalu and Steen [18] found that the cutting speed increases proportionally to the gas jet velocity up to a particular value after which the cutting speed falls off when the nozzle pressure increases.

The present work follows the lead of Hsu and Molian [3], who introduced the combustion effect in cutting of steel using high power lasers. This model is applied for cutting of austenitic steel of 0.5 and 2mm sheet thicknesses with low power laser. The effect of gas pressure on the cutting speed has also been studied. The effects of combustion and the laser power are studied through a comparison of experimental and theoretical results.

Theoretical Modeling

Hsu and Molian [3] repoted laser cutting model in the which they have calculated combustion and laser power densities contributing in cutting of thick steel i.e., 1-10mm and used laser power 1 to 1.5 kW CO_2 laser. This model was developed on the basis of classical heat conduction theory of Carslaw and Jaeger [19]. The different symbols used in model are listed below:

A	Absorptivity	a	Focused laser beam diameter (m)
I	Laser power density (W cm^{-2})	K	Thermal conductivity ($Wm^{-1}K^{-1}$)
K_0	Modified Bessel function of the second kind and zeroth order	S	Normalized speed
		l	Thickness of material (m)
T(x,y)	Temperature at (x,y) (K)		
V	Cutting speed (ms^{-1})	R	Half of kerf width (m)
P	Laser power (W)	η	Combustion efficiency
ΔH	Heat of combustion (J Kg^{-1})	α	Thermal diffusivity (m^2s^{-1})
δ	Average thickness of liquid melts film (m)	ρ	Material density (Kg m^{-3})

The expression introduced by Carslaw and Jaeger [19] for moving heating point source can be written into polar co-ordinates as:

$$T(x,y) = T_0 + \frac{1}{2\pi lK} \int I_{total} r dr \int e^{\frac{V(x-r\cos\theta)}{2\alpha}} \left\{ K_0 \frac{V\sqrt{(x-r\cos\theta)^2+(y-r\sin\theta)^2}}{2\alpha} \right\} d\theta \qquad (1)$$

where r, θ are polar coordinates.
In the above expression "I_{total}" is the total power density supplied to the metal for cutting which is a combination of laser and combustion power densities and can be expressed as:

$$I_{total} = I_{Laser} + I_{Comb.} \qquad (2)$$

Where "I_{Laser}" for a Gaussian mode CO_2 laser beam, the power density is

$$I_{Laser} = \frac{8P}{\pi \cdot a^2} \exp(-8r^2/a^2) \qquad (3)$$

and the power density from combustion "I_{comb}" can be expressed as

$$I_{Comb} = \frac{V\rho l \Delta H}{\delta} \qquad (4)$$

$$I_{Comb} = \frac{\rho l \Delta H (2\alpha) S}{\delta R} \qquad (5)$$

where $S = \frac{VR}{2\alpha}$ is a normalized working speed.

Equation 1 can be simplified by using Eq. 2, Eq.3 and Eq. 4a and the final expression for the melting temperature is given by [3]:

$$T_{mp} = T_0 + \frac{AR^2}{2\pi lK(1-e^{-2})} I_{Laser} + \frac{\eta R^2}{2\pi lK} I_{Comb.} \qquad (6)$$

Where I_{laser} and $I_{Comb.}$ are given by the equations as:

$$I_{Laser} = \int_0^{a/2R} \left(\frac{8P}{\pi a^2}\right) e^{\left(\frac{-8R^2 r_1{}^2}{a^2}\right)} r_1 dr_1 \int_0^{2\pi} e^{\frac{-S\, r_1 \cos\theta}{2\alpha}} \left(K_0 S\sqrt{r_1{}^2 - 2r_1 \sin\theta + 1}\right) d\theta \qquad (7)$$

and $$I_{Comb.} = \int_{\frac{a}{R}}^{1+\delta/2R} \left(\frac{2\alpha\rho l(\Delta H)}{R\delta}\right) r_1 dr_1 \int_{\frac{\pi}{2}}^{3\frac{\pi}{2}} e^{\frac{-S\, r_1 \cos\theta}{2\alpha}} \left(K_0 S\sqrt{r_1{}^2 - 2r_1 \sin\theta + 1}\right) d\theta \qquad (8)$$

The values of the constants used in our calculations are; $T_0 = 300$ K, material density = 7877 Kg m^{-3}, thermal conductivity = 31.3 W $m^{-1}K^{-1}$, thermal diffusivity = $3.42x10^{-6}$ m^2s^{-1}, heat of combustion = 63.2 kcal/mole.

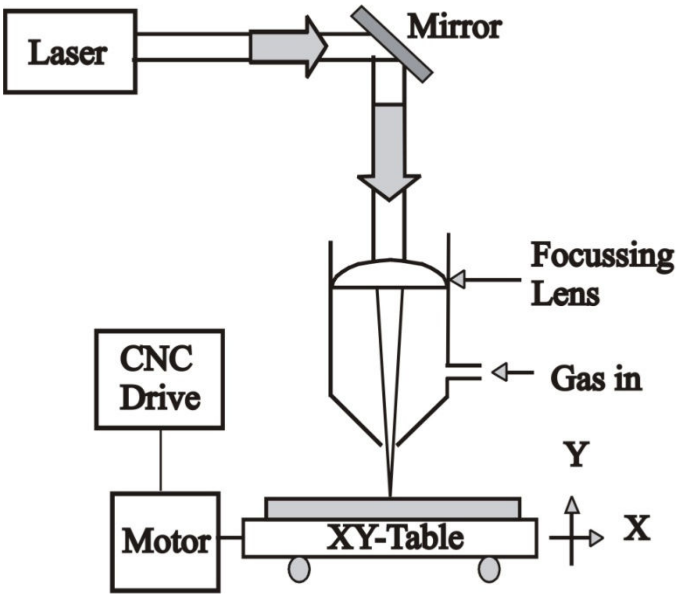

Fig. 1 Experimental setup for laser cutting process.

Experimental Techniques

A continuous wave CO_2 laser of 200 ~300 W was used to cut the austenitic stainless steel of 0.5 mm and 2 mm sheet thickness with oxygen, compressed air and nitrogen as assist gases. The mode pattern of laser beam exhibits a TEM_{00}. The laser beam was reflected at 90° and then focused on the work piece by means of a lens with a focal length of 127mm. The focused spot size was o.2 mm. The focal point was set on the surface of the work piece. A convergent nozzle of diameter 1 mm was used for oxygen flow at the exit point. The work piece was fixed onto a computer controlled CNC worktable which moved under the laser beam. The maximum speed was determined for each material and for each assist gas. The kerf width was measured with an optical microscope having the value as 0.3 mm.

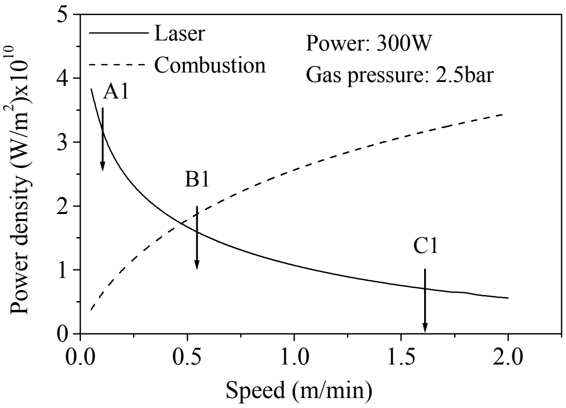

Fig. 2 Power density vs cutting speed for 0.5mm steel.

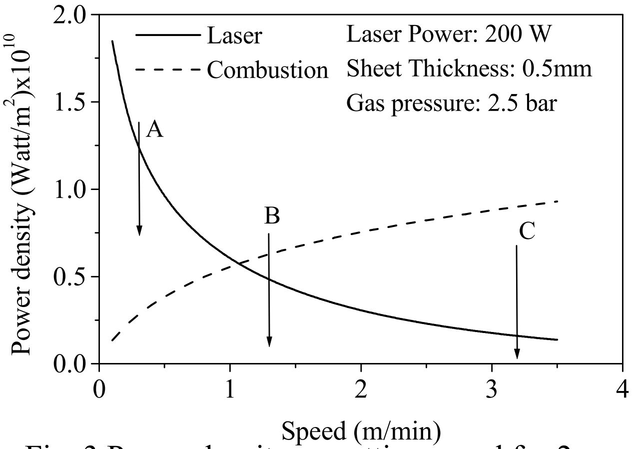

Fig. 3 Power density vs cutting speed for 2mm steel.

Results and Discussions

Laser and combustion power densities are calculated from Eq. 7 and Eq. 8 and plotted as a function of cutting speed for 0.5 and 2 mm thick sheets as shown in Fig. 2 and Fig. 3, respectively. The arrows A, B and C in the Fig. 2 indicate the maximum cutting speed (experimental) for nitrogen, compressed air and oxygen respectively. Similarly the arrows A1, B1 and C1 in Fig. 3 show the maximum cutting speed measured experimentally for three gases respectively. The laser power density decreases exponentially with speed where as combustion power density increases exponentially with cutting speed. The contribution of combustion power density overtakes the laser power density at higher speeds. It is due to the fact that the oxygen reacts with the cut front exothermally, providing extra amount of heat energy for melting. This energy depends upon the thermal properties of the material and cutting speed. The melting zone is divided into two parts: one is the kerf width and second is the average thickness of the liquid melt film, "δ" attached to the cutting edge. The film thickness "δ" varies with the increase of sheet thickness for optimum cutting parameters in the range from 0 to 0.1mm [21]. The absorptivity of carbon steel, subject to 10.6µm wavelength irradiation, increases significantly for peak powers > 10^7 Wcm^{-2} and it depends on the surface condition of the materials [22]. The absorptivity of 80% is taken for CO_2 laser in cutting of stainless steel and used in our model. Ivarson et. al. [11] have reported that 50% of iron in laser cutting of steel had oxidized in FeO confirmed by Atara [20], therefore, η=50% was used in our model. The temperature generated by the contribution of laser and combustion energies of the cut front as predicted from Eq. 6 is given in Fig. 4. It gives the theoretical variations of temperature against the cutting speed for 2mm steel and confirms that the temperature is well above the melting point of the material. Similar behavior is also observed for 0.5 mm thickness steel. The percentage increase in the contribution of combustion power density in laser cutting as shown in Fig. 2 and Fig. 3 can be calculated by:

$$\%increase = \left(\frac{I_{Comb} - I_{Laser}}{I_{Comb}}\right) x100.$$

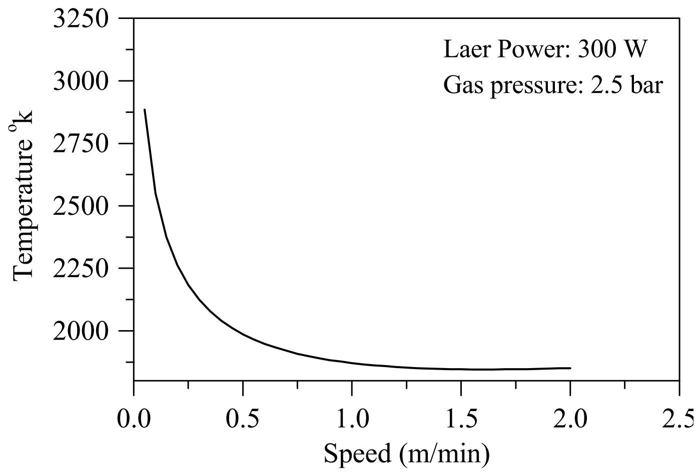

Fig. 4 The variation of temperature with cutting for 2 mm steel sheet.

At the maximum cutting speed for 2mm sheet the %age increase in the combustion energy is about 78% and for 0.5mm sheet it is about 82% which is obvious from the above two figures. The cutting speed with compressed air and nitrogen drastically lowers down as compared to oxygen, as given in the Table-1.

The nitrogen does not react with steel/iron and only laser power is used to melt the material. The melting of 2mm and 0.5mm thick sheets follow the curves "laser power densities" only as given in Fig. 2 and Fig. 3, respectively. The nitrogen gas is used only to eject the molten material from kerf width, where as compressed air consists of a number of gases, mainly nitrogen, oxygen, carbon dioxide and etc. When the compressed air is used as an assist gas for this process, oxygen present in it reacts with steel and starts combustion process and provides some additional amount of energy for melting. As a result, the cutting speed is increased from 100mm/min to 500mm/min for 2mm steel. Similarly, for 0.5mm sheet thickness, the processing speed increases from 300 mm/min to 1200mm/min as compared to nitrogen. The contribution of combustion energy in this case is small relative to use of pure oxygen.

Table 1 Laser cutting data of 2 mm and 0.5 mm thick steel for three assist gases

Sr. No	Sheet thickness, mm	Laser Power W	Assist gas (Gas pressure: 2.5 bar)	Processing speed m/min
1	2	300	Oxygen	1.6
2	2	300	Compressed Air	0.5
3	2	300	Nitrogen	0.1
4	0.5	200	Oxygen	3.2
5	0.5	200	Compressed Air	1.2
6	0.5	200	Nitrogen	0.3

The variation of kerf width with working speed for 0.5mm steel in which oxygen and compressed gases are used as an assist gases, shown in Fig. 5. The kerf width decreases with increasing the processing speed in both cases. It is due to the fact that, at lower speed, more heat energy is deposited in the material for melting which melts more area resulting in large kerf width. Therefore, the kerf width decreases with working speed until a critical/optimum speed is achieved where the kerf width becomes constant. The kerf width increases with gas pressure at constant speed and power as given in Fig. 6. The effects of oxygen gas pressure on maximum cutting with constant laser power for specific sheet thickness are shown in Fig. 7. The increase in kerf width and maximum cutting speed with gas pressure may be discussed in two ways, i.e., one is additional contribution of combustion energy and second is high dragging force. The increase in kerf width and speed is the outcome of increased melting due to additional amount of heat energy supplied through combustion process. The high drag force of high pressure gas flow may be due to the increase in the maximum cutting speed as reported in [9].

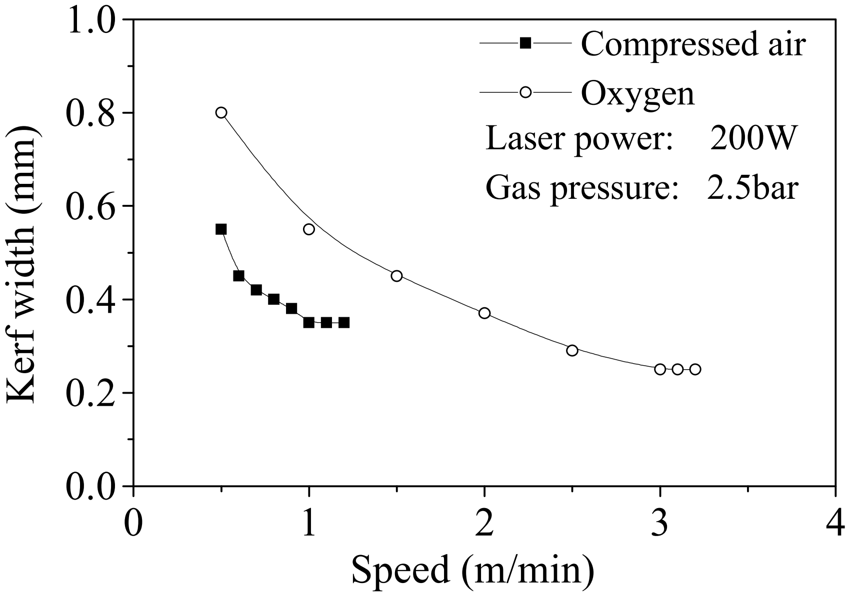

Fig. 5 The variation of kerf width with cutting speed for 0.5 mm sheet.

Comparing the theoretical results as shown in Fig. 2 and Fig. 3, and the experimental results shown in the Table 1, it can be seen that the contribution of combustion energy is about 82% and 77% for 0.5mm and 2mm sheet respectively which agrees with the increased speed in laser cutting with oxygen as assist gas.

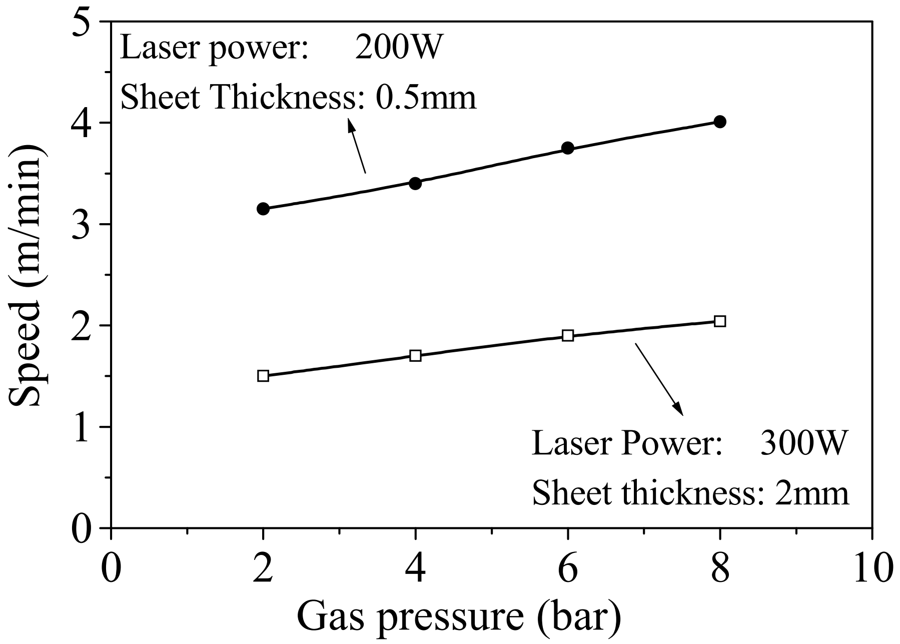

Fig. 6 Variation of kerf width with gas pressure.

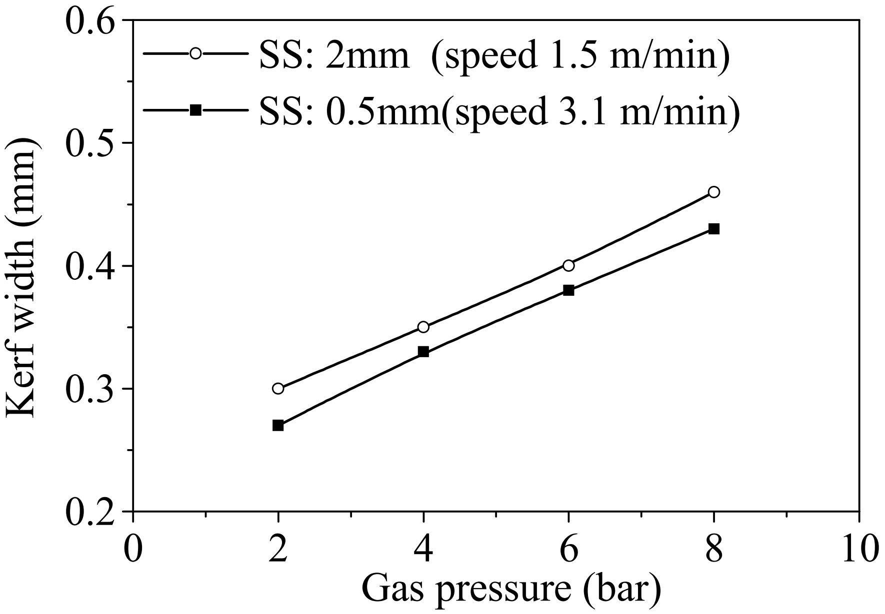

Fig. 7 Variation of cutting speed with oxygen gas pressure.

Conclusions

Laser cutting of 0.5mm and 2mm thick austenitic stainless steel has been carried out using oxygen, nitrogen and compressed air as assist gases. The contribution of laser and combustion energies in this process are calculated. The effect of combustion energy is found to be more than 80 % as compared to the other assist gasses. The kerf width decreases with increasing the speed for specific laser power and gas pressure. The processing speed and kerf width increases with oxygen gas pressure.

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