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Physics Procedia 39 (2012) 179 – 185

Physics Procedia

LANE 2012

Dynamic phenomena in laser cutting and process performance

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- Invited Paper -

Abstract

Laser cutting of sheet metals is widely used all over the world since it combines high speed with excellent cutting quality. Nevertheless if the thickness of the work piece becomes relatively high, the roughness of the cut edges becomes quite coarse and also the formation of dross and slag is likely. The latter phenomena must obviously be related to dynamic processes that can be identified as fluctuations in the liquid body that forms at the current end of the cut due to absorption of laser radiation and where material removal takes place due to friction with a sharply focused gas jet. A detailed analysis of the liquid layer shows that viscosity and surface tension that have so far not been considered very often in the literature have a strong impact on the material removal mechanism which consists of the formation and separation of droplets formed at the bottom of the work piece, thus being essentially intermittent. The mathematical treatment of this model shows good coincidence with experimental data. It gives rise to the idea that a substantial reduction of surface tension could improve the material removal mechanism insofar as the intermittent ejection is transformed into a continuous ejection of melt flow thus considerably improving cutting speed and quality. These ideas have also led to a new patent for an improved laser cutting head.

Keywords: Laser cutting; cut quality; intermittent melt removal; surface tension

1. Introduction

In laser cutting, the laser beam hits the work piece at the current end of the cut kerf (Fig.1) and heats the material. This process forms a thin liquid layer that is slightly inclined towards the vertical direction. Material removal is performed by a sharply focused gas jet, which we assume to be of subsonic velocity, that hits the liquid layer and exerts a shear stress on it that leads to material removal at the bottom of the

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 doi:10.1016/j.phpro.2012.10.028

work piece. The gas jet usually contains oxygen and therefore an exothermic reaction with the liquid material (e.g. steel) leads to additional heating. Due to this mechanism of laser cutting, the liquid layer points out to be the actual cutting tool since all relevant processes take place there.

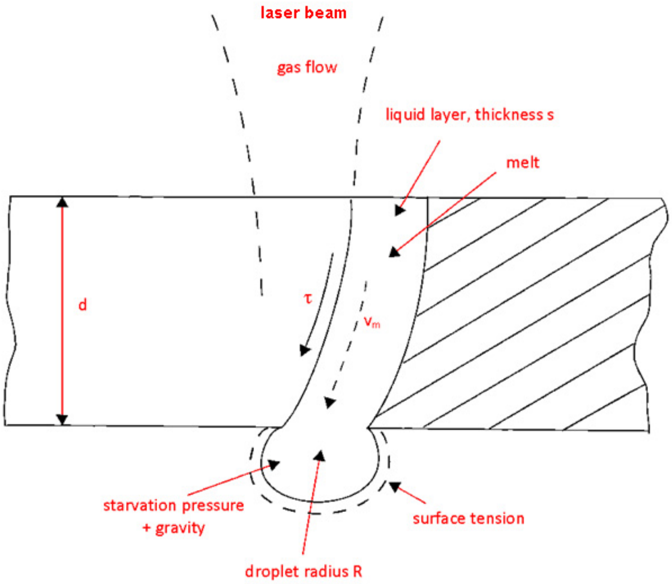

Fig. 1. Cross section of a work piece partly cut with a laser, left view into the kerf, middle molten layer with mass flow, right part still uncut material

The process of laser cutting is nowadays a well established industrial process. Yet there is still active research being done on this topic (e.g. in [2]). This paper tries to encourage a deeper analysis of what actually happens in the cut kerf which the authors think to be necessary to further improve cut quality and diminish the probability of adherent dross or slag (Fig. 2) that make time-consuming follow-up treatment necessary.

Fig. 2. Example of quality defects on a workpiece

The model presented in this paper focuses on the formation of droplets of molten material on the lower side of the workpiece caused by the shear stress τ exerted by the assisting gas jet on the surface of the molten zone as depicted in Fig. 1. The authors claim that this stress leads to a downward flow within the molten metal and thus a buildup of droplets on the bottom side. These droplets separate from the workpiece when the surface tension of the droplet is overcome by the starvation pressure caused by said flow. Furthermore the authors believe that there is a connection between the inverse of the time needed for a droplet to form and the frequency of striations on the workpiece (Fig. 2). This conjecture seems to be in accordance with experimental data obtained by the authors.

2. Dynamic model

In order to understand the influence of process parameters such as laser power, gas jet speed and pressure and processing speed as well as work piece properties, a steady state analysis of the liquid body can be carried out. Since the inner structure of the body is unknown, only balance equation as for energy, mass and momentum can be used. It has been shown in the past, that with these equations the dependence of cutting speed on laser power, work piece thickness, etc. can be explained satisfactorily. Nevertheless a dynamic analysis is necessary since the quality defects are caused obviously by time dependent effects.

The shear stress τ is given in the following equation. Originally, this result is due to [1]. With $\boldsymbol{\rho_g}$ we denote the gas jet's density and $\boldsymbol{\mu_g}$ its (dynamic) viscosity. Please note that throughout this paper, when we speak of viscosity, we always mean the dynamic viscosity. Furthermore let d be the work piece's thickness and $\boldsymbol{v_g}$ the gas jet's speed.

$$\tau = \sqrt{\frac{\rho_g \cdot \mu_g \cdot v_g^3}{d}} \tag{1}$$

This stress induces a movement in the molten material towards the bottom of the workpiece that depends on the melt's viscosity μ_m, the liquid layer's thickness s and is given by

$$v_m = \frac{s \cdot \tau}{\mu_m} \tag{2}$$

The material cannot leave the liquid body at the lower side due to surface tension and so a droplet forms that grows in time in a process quite similar to a leaking water tap. Due to the permanent flow of water into the droplet, the mass of the droplet increases and so does its internal pressure. The radius of the droplet also rises which means that surface tension decreases. Eventually the internal pressure overcomes the surface tension and the droplet leaves the tap and so the next droplet begins to form.

Let σ denote the molten materials surface tension constant, R the radius of the forming droplet which we assume to be of half-cylindrical shape. Let p_G be the weight of the forming droplet and p_S the melt flow's starvation pressure. There ρ_m denotes the melt's density.

$$p_G = \frac{1}{2}\rho_m \cdot g \cdot R \tag{3}$$

$$p_S = \frac{v_m^2 \cdot \rho_m}{2} \tag{4}$$

A droplet separates when the sum of $p_G + p_S$ overcome the pressure p_σ given by

$$p_\sigma = \frac{\sigma}{R} \tag{5}$$

If we denote the cut kerf's width by w and the molten zone's thickness by s, we can calculate the mass flow into the forming droplet through the area $A = s \cdot w$. This leads to the following formula for the radius R.

$$R(t) = \sqrt{\frac{1}{2\pi} \cdot s \cdot v_m \cdot t} \tag{6}$$

If we now combine equations (3), (4), (5) we get the pressure balance inside the droplet:

$$\frac{2\sigma}{R} = \frac{1}{2} \cdot \rho_m \cdot g \cdot R + \frac{{v_m}^2 \cdot \rho_m}{2} \tag{7}$$

If we now insert R(t) into equation (7) and solve for t, we can calculate an estimate for the time needed for a single droplet to separate from the workpiece. Its inverse f is the droplet formation frequency. By multiplying this frequency with the overall cutting speed v, we get what we call the striation wavelength λ.

Periodic formation and deliberation of droplets takes place which leads to a more or less periodic process where the mass of the liquid layer and also its volume rise during the formation of the droplet and after its deliberation mass and volume of the liquid layer are suddenly reduced. Therefore material removal takes place in an intermittent way which seems to be in accordance with experimental results.

The calculations were carried out using Mathematica. For our work we used common S235-steel with a thickness of 8 mm as a sample. We estimated the thickness of the molten zone s by a simple analytic solution of the (linear) heat conduction equation. For details please refer to [5]. Table 1 shows the constants used in our calculations. Values for the surface tension constant for iron-oxygen alloys are taken from [3].

Table 1. Material constants

Viscosity of molten material	$\mu_m = 5.443 \cdot 10^{-3} \frac{Ns}{m^2}$
Density of gas jet	$\rho_g = 1.429 \frac{kg}{m^3}$
Density of molten material (average between steel and its oxides)	$\rho_m = 5.24 \cdot 10^3 \frac{kg}{m^3}$
Velocity of gas jet	$v_g = 301 \frac{m}{s}$
Viscosity of gas jet	$\mu_g = 19.2 \cdot 10^{-6} \frac{Ns}{m^2}$
Surface tension of molten material	$\sigma_m = 1918 \frac{N}{m}$

In the following table we compare the computed values with a value for λ experimentally obtained by G. Schuöcker at Svoent.

Table 2. Numerical results compared to the experiment

Quantity	Unit	Value	Value
d	m	0,002	0,008
s	$10^{-6} m$	150	200
v_m	$\frac{m}{s}$	33,71	22,47
t_{drop}	s	0,00052	0,0029
R	m	0,0013	0,00029
f	Hz	1939,8	340,7
v	$\frac{m}{s}$	0,1333	0,1167
λ	m	0,000069	0,00034
λ_{exp}	m	0,00005	0,0003

3. Cut quality defects and cutting performance improvements

As far as it concerns dross and slag, the dynamic model developed above also gives rise to an explanation. Since the liquid layer has a moon like shape (Fig. 3) with a large thickness in the middle of the kerf and much lower thickness at the cut edges, the surface tension shows a minimum value in the center of the kerf and rises towards the walls of the kerf. So it's plausible that the equality between surface tension and internal pressure that causes the separation of the droplet is reached earlier in the center of the cut kerf than at the edges. This means that deliberation of the droplet will be most likely take place in the center of the liquid body. In this case liquid material will leave the work piece in the center of the kerf. Nevertheless if for any reason the gas jet is declined towards one of the cut edges, the shear stress will become much stronger there and thus the balance between surface tension and internal pressure can be reached earlier than in the center of the kerf and a droplet is deliberated at the cut edge, what means that liquid material flows along the cut edge to the bottom of the work piece thus making adherent dross and slag much likely.

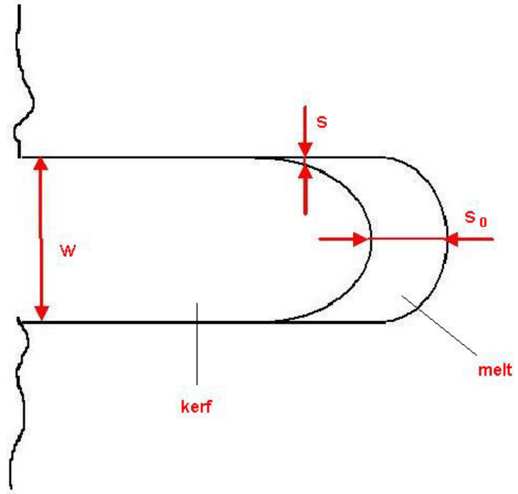

Fig. 3. Horizontal cross section of the molten layer

Based on the above considerations, it can be argued that a substantial reduction of surface tension must influence laser cutting performance considerably: First such a reduction of surface tension would possibly enhance the cut quality since it makes the defects discussed above less likely. Moreover with a substantial reduction of surface tension the drop wise ejection of liquid material could be turned to a continuous flow of material out of the work piece at its bottom probably resulting in a strongly increased maximum cutting speed.

In order to realize the latter ideas a new cutting head has been designed where an auxiliary nozzle is used to blow a certain material as for instance sulfur on the surface of the liquid layer thus reducing its surface tension. An Austrian Patent with the number 509911 has been granted for this cutting head.

4. Conclusion

In this paper, the authors presented a new model for the dynamic behavior of the liquid layer in laser cutting that predicts intermittent melt ejection. This is experimentally justified by a well known phenomenon, the spark shower, consisting of molten droplets. This model hints at a connection between this intermittent droplet ejection and the formation of periodic striations along the cut edges and also gives a reasonable explanation for the formation of adherent slag. Both phenomena are (severe) quality defects. Further research is necessary into a refined mathematical formulation of the above model and into the idea of continuous melt ejection which the authors think would immensely increase cutting speed and cut quality. Another topic of interest to the authors is the role surface tension plays in the process of laser cutting and whether a significant reduction can also increase quality and speed of the cutting process.

Acknowledgments

The authors are indebted to ACCM – Austrian Center of Competence in Mechatronics Linz for financial support and to Georg Schuöcker / Svoboda Entwicklungs GmbH in St. Pölten for extensive measurements, especially of the striation frequency.

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