DYNAMIC PHENOMENA AND QUALITY DEFECTS IN LASER CUTTING

Dieter Schuöcker[(a)], Joachim Aichinger[(b)], Georg Schuöcker[(c)]

[(a)]Upper Austrian Laser Center
[(b)]Upper Austrian Laser Center
[(c)]Svoent Entwicklungs GmbH & CO KG

[(a)]dschuoecker@ooelz.at, [(b)]jaichinger@ooelz.at, [(c)]georg.schuoecker@svoboda.at

ABSTRACT
If relatively thick workpieces are cut with a laser severe quality defects appear as enhanced roughness and adherent slag. The latter quality degradations must be caused by dynamic phenomena taking place in the liquid layer formed at the momentary end of the cut kerf. Therefore a theoretical analysis of the latter zone has been carried out that shows that surface tension plays a major role and causes an intermittent ejection of melt that is finally responsible for fluctuations of the volume of the molten body leading to roughness of the cuts. The latter intermittent melt removal can also be shown to cause adherent dross and slag. A mathematical evaluation of the latter considerations shows good coincidence with experiments.

Keywords: laser cutting, laser cut quality, modeling of laser cutting, dynamics of laser cutting

1. INTRODUCTION

Laser cutting is a most advanced technology for shaping sheet metals. Nevertheless in the case of thick workpieces certain quality defects can be observed as for instance cut edge roughness and irregularities and also adherent material as dross and slag (see Figure 1).

These effects can be caused by inappropriate parameters but also may have their origin in distortions going out from the various modules of the laser cutting system as the laser source, the motion system and the CNC control. In order to clarify the latter phenomena not only modeling of the cutting process itself, as usually done by many research groups, but also of the complete cutting system is ultimately necessary and has been tackled at the Upper Austrian Laser Center beginning with an improved model of the interaction process.

Laser cutting is governed to a large extent by the temperature distribution built up by a high power laser beam moving over the surface of the work piece. The latter temperature distribution results from the solution of the heat conduction equation. The solution of the latter is very complex since the thermal parameters involved depend on the temperature and so the differential equation is highly nonlinear. Nevertheless G. Herziger, one of the most prominent laser scientists from the RWTH Aachen, has shown, that using average values for the relevant parameters as thermal conductivity, thermal diffusity, specific heat and so on introduces only an error of a few percent into the solution of the heat conduction equation and therefore the temperature dependent relevant parameters can be replaced by average values. Therefore the heat conduction equation can be solved in an analytical way without the necessity of FEM-simulations, thus yielding analytical models for laser cutting. Models of that kind have been developed in the EU countries, in Russia, Japan and the USA.

Figure 1: Periodic Striations and Adherent Material at the Cut Edges, 8mm Steel

The distortions of workpiece quality must be related to dynamic phenomena appearing during laser cutting. So far the time dependent behavior of laser cutting has not been analyzed very often since most of the theoretical descriptions of laser cutting restrict themselves to steady state conditions. Nevertheless to be able to understand the dynamics of the process first the mechanism of continuous laser cutting, that means continuous cutting with constant high quality must be understood. Therefore in the first main part of the actual paper the mechanism of laser cutting and the geometry of the process will be explained. These considerations will show that at the momentary end of the cut kerf where the laser beam and a sharply focused jet of process gas hits the workpiece a thin liquid layer is formed, that extends in vertical direction throughout the full depth of the workpiece. So far the phenomena appearing in this molten zone are not well understood and thus in the second main part of the paper the behavior of this region including dynamic phenomena will be analyzed in detail yielding an explanation for the formation of the well known striation pattern on the cut edges that leads to a certain roughness and also a model for the mechanism of the formation of adherent material at the cut edge. It will be shown that nice coincidence exists between theoretical outcomings and experimental results.

2. MECHANISM OF STEADY STATE LASER CUTTING

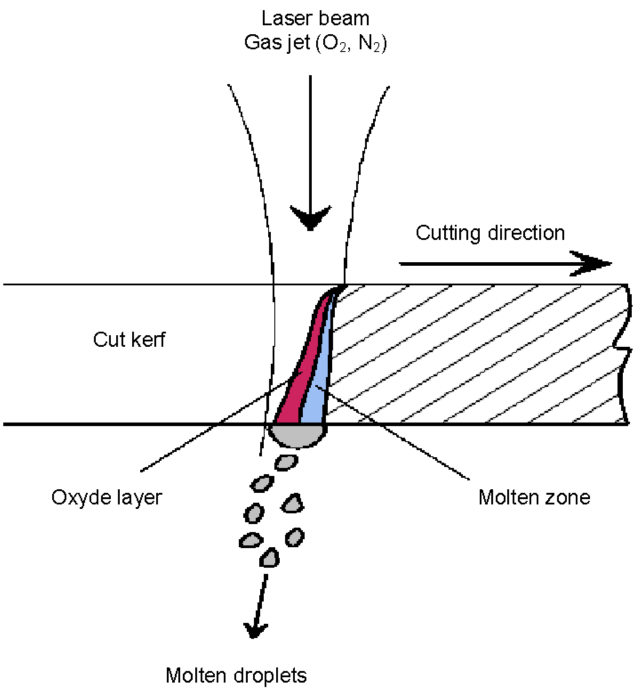

Figure 2: The Mechanism of Laser Cutting

Figure 2 shows a cross section of a work piece that has partly been cut whereas on the left hand side the kerf has been formed and on the right hand side the material is still uncut. At the momentary end of the cut kerf the laser beam and also a sharply focused jet of process gas preferably a mixture of oxygen and nitrogen usually deviating from the composition of air impinge on the workpiece. The laser beam is absorbed to some part by the momentary end of the cut and heats the material, finally leading to the formation of a thin molten layer that extends throughout the full depth of the workpiece. Moreover the oxygen content of the gas jet mentioned before, that hits the surface of the molten layer leads to the generation of additional heat by reaction. Due to the friction between the gas jet and the molten material, melt is ejected at the bottom of the workpiece thus leading to the material removal necessary for laser cutting. The liquid layer moves with the laser beam and the gas jet in cutting direction and melts solid material at the interface between melt and solid and compensates thus the material losses due to ejection at the bottom of the workpiece as mentioned before. So all phenomena necessary for laser cutting take place in the molten zone as absorption of laser radiation, generation of reaction heat, heating and melting of the solid material and ejection of liquid material at the bottom of the workpiece and therefore the liquid layer can be regarded as the actual cutting tool. It moves through the workpiece and in the case of steady state cutting without any distortions of its volume, mass and temperature. A mathematical description of steady state laser cutting as described above must rely on balance equations as for the energy, for momentum and for mass since the internal structure and the mechanisms that take place in the liquid layer are unknown. In the next part of the actual paper it will be shown that there are time dependent phenomena associated to the liquid layer and playing an important role. With the description of these dynamic phenomena a possible explanation for the formation of a very rough surface structure and also of adherent material as dross and slag on the cut edges especially for the case of relatively thick workpieces can be found.

3. DYNAMIC BEHAVIOR OF THE MOLTEN LAYER

The molten layer that is located at the momentary end of the cut kerf as mentioned above is subject to friction with the cutting gas flow, that exerts a shear stress τ on the liquid body The latter depends on the viscosity of the cutting gas η, the density of the latter ρ, its speed v being equal to the speed of sound if a regular nozzle and not a laval nozzle is assumed. and the thickness of the workpiece d (Vicanek and Simon 1987):

$$\tau = Sqrt(\eta \rho v^3 / d) \tag{1}$$

To get the force acting on the liquid layer, the latter expression must be multiplied by the surface of the liquid layer given by the width of the kerf w and the thickness of the work piece. This force has a magnitude of 2 N/m^2 . The latter force accelerates the molten material according to

$$\frac{d_{melt}}{dt} = \rho_m dw \frac{s}{2} \cdot \tau wd \tag{2}$$

where ρ_m is the density of the molten material. The use of s/2 instead of s in the accelerated mass will be justified later.

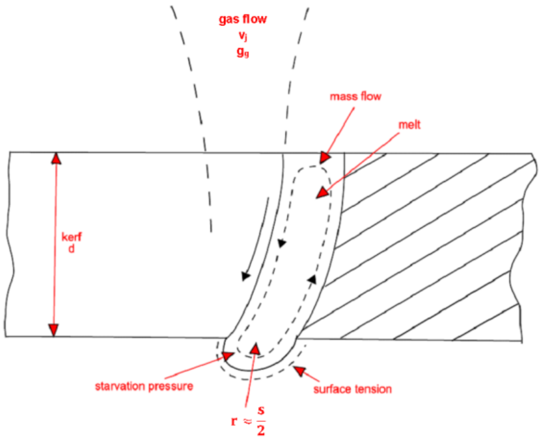

Figure 3: Cross Section of a Workpiece Partly Cut with a Laser, Left View Into the Kerf, Middle Molten Layer with Closed Loop Mass Flow, Right Part Still Uncut Material.

Due to the motion given by equation (2), the melt flows in an downward direction (Figure 3), but cannot leave the workpiece since the hydrostatic pressure in the melt is usually much smaller than the surface tension at the bottom of the liquid body. Therefore the melt flow must reverse there and flow in an upward direction, thus becoming a closed loop flow. The extension of both flows, downward and upward, is then half of the thickness of the liquid layer s/2.Since this mass flow is permanently accelerated by friction with the cutting gas, its speed v_{melt} rises and so does the starvation pressure p_{starv} built up at the bottom of the liquid body

$$p_{starv} = \rho_{melt} v_{melt}{}^2 / 2 \qquad (3)$$

The latter pressure serves for the reversal of the melt flow direction.

The latter pressure adds to the hydrostatic pressure

$$p_{stat} = \rho_{melt} dg \qquad (4)$$

The magnitude of the latter pressure is 1000 N/m^2, much smaller than the surface tension

$$p_{\sigma} = 2\frac{\sigma}{r} \qquad (5)$$

with r being the radius of curvature at the bottom of the liquid layer and approximately equal to s/2. An upper limit for the latter pressure is 100.000 N/m^2.

With permanently rising melt flow speed, eventually the starvation pressure will reach the surface tension, thus breaking up the surface skin and allowing the ejection of liquid material.

From the above equations, the time where this event takes place can be calculated:

$$T_{off} = \sqrt{\rho_{melt}}\, s \frac{1}{\tau} \sqrt{2 p_{\sigma} / s} \qquad (6)$$

For steel with d=8 mm , v=2m/s and a laser power of 3kW, equation 6 yields T_{off} =0.0076 s.

Due to the outflow of material in the opening in the bottom skin of the liquid layer the mass in the latter is reduced and thus also the pressure must decrease what means that after a short time the surface tension again prevails and the bottom skin closes and thus the outflow of material is interrupted, what means a new sequence as described here starts. The duration of the latter melt flow is given by the time needed by the melt to flow through the full vertical extension of the molten layer

$$T_{on} = \frac{d}{v_{melt}} \qquad (7)$$

For the example treated before, T_{on}=0.0028 s.

With T_{off} and T_{on}, the frequency of the sequence of breaking and reestablishment of the surface tension is given by

$$f_{meltflow} = \frac{1}{T_{off} + T_{on}} \qquad (8)$$

Since the mass and the volume of the liquid layer change during the above sequence it can be argued that also the width of the liquid layer changes and thus a pattern of periodic striations is generated on the cut edges. Equation (8) yields for the above example a striation frequency of 96 Hz, where experiments showed 130 Hz. Measurements for d=4mm, v=3m/min yield a striation frequency of roughly 380Hz, what confirms the theoretical tendency of the latter frequency to increase with decreasing workpiece thickness or the fact, that the roughness becomes smaller for thin workpieces.

It should be mentioned that various authors have developed models for the mechanism leading to periodic distortions on cut edges as for instance based on oscillations of the molten body (Schuöcker, 1986), waves on the melt surface (Chen and Yao, 1999) , cyclic reaction (Ivarson, Powell, Kamalu, and Magnusson, 1994) and others. Fundamental work on the above topic has been carried out by Arata (Arata, Maruo, Miyamoto, and Takeuchi, 1979). All these models describe mechanisms that apply to specific situations e.g. Schuöcker treats cutting with and without oxygen content in the process gas whereas Ivarson and Ermolaev (Ermolaev, Kovalev, Orishich, and Fomin, 2006) apply only to reactive gas assisted laser cutting.

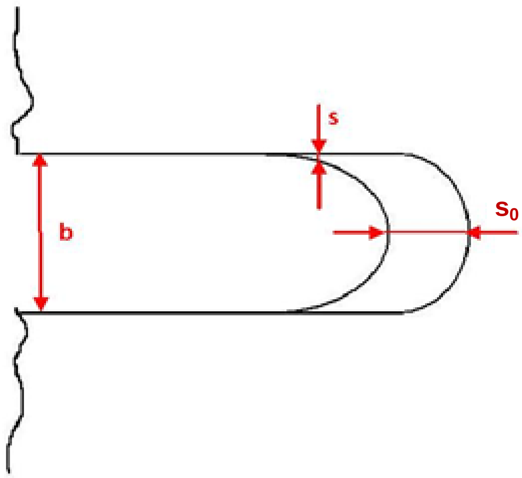

Figure 4: Cut Kerf with Molten Layer, seen from above

Following these considerations it can be argued that the condition for breaking up of the bottom surface skin at the molten layer near the kerf walls, the cut edges might be considerably different from the conditions in the case of the middle of the liquid layer as treated above, since at least the thickness of the liquid layer s is considerably smaller (see Figure 4). So it might happen that the bottom skin of the liquid layer breaks up earlier near the walls of the kerf than in the middle of the liquid layer (see Equation 6). In this case liquid material will also leave the molten body but in the case treated here it will flow along the walls of the kerf. In this case after the liquid material has left the molten body it may adhere at the kerf walls and this means the establishment of dross totally unwanted in laser cutting since it makes a post processing with big expenses necessary.

The latter considerations mean that the condition for breaking up the surface skin of the liquid layer takes place after a shorter time than for the central part. Nevertheless melt flow is in direct contact with the mass flow in the center of the liquid body and so the flow-speed will not change too much if one moves from the center of the liquid layer to the wall-near regions. With s_0 being the thickness of the molten layer in the center of the melt, Eq. 6 writes then

$$T = \sqrt{\rho_{melt}}\, s_0 \frac{1}{\tau} \sqrt{2 p_\sigma / s} \qquad (9)$$

So the breaking up of the surface tension is reached later near the walls with smaller s, that means usually the burst of liquid material out of the molten body will take place just in the center of the kerf. Nevertheless the liquid body is an unstable entity and may change its geometry especially in the center of the kerf in such a way that the point of equality between the starvation pressure and the surface tension is reached earlier in the wall-near zones of the liquid body and so the process will leave melt just at the walls and may then incline to form dross.

Coming back to the quasistationary performance of the melt body as mentioned in chapter 2, the average speed of melt ejection can now be determined from v_{melt}, T_{open} and $f_{meltflow}$, allowing to calculate the mass loss per second of the molten body

$$\left(\frac{dm}{dt}\right)_{melt} = s w_k \rho_{melt} v_{melt} T_{on} f_{melt} \qquad (10)$$

Again, the above example is used and yields for the above mass loss 0.00092 kg/s.

This can be compared to the mass molten per unit time and given by

$$\left(\frac{dm}{dt}\right)_{solid} = d w_k \rho_{melt} v \qquad (11)$$

v cutting speed. Again, for the above example, Equation (11) yields a mass gain of the liquid of 0.0008 kg/s, what agrees roughly to the mass loss of the liquid and justifies the assumption made for the thickness of the liquid layer.

The above considerations clearly show that the reasons for the intermittent mass ejection described here are a relatively weak friction between the process gas flow and the surface of the molten layer and a predominant surface tension causing a rough structure on the cut edge. Further on it has been shown that the main reason for adherent material as dross and slag is related to melt ejection not in the middle of the kerf but on the walls of the kerf. Based on these outcomings measures have been proposed in order to improve cutting quality, especially in view of a fine surface structure on the cut edge, leading to reduced roughness and the absence of dross and slag. The latter concept is subject to patent application (Schuöcker 2010).

LIST OF REFERENCES

Arata, Y, Maruo, H, Miyamoto, I, Takeuchi, S, 1979. Dynamic Behavior in Laser Gas Cutting of Mild Steel. *Transactions of JWRI* Vol.8,No.2: 15-26

Chen, K, Yao, Y L, 1999. Striation Formation and Melt Removal in the Laser Cutting Process. Journal of Manufacturing Processes Vol.1/No.1: 43-53

Ermaolaev, G V, Kovalev, O B, Orishick, A M, Fomin, V M, 2006. Mathematical modeling of striation formation in oxygen laser cutting of mild steel. *Journal of Physics D: Applied Physics* 39: 4236-4244

Ivarson, A, Powell, J, Kamalu, J, Magnusson, C, 1994. The oxidation dynamics of laser cutting of mild steel and the generation of striations on the cut edge. *Journal of Materials Processing Technology* 40: 359-374

Schuöcker, D, 1986. Dynamic Phenomena in Laser Cutting and Cut Quality. *Applied Physics B: Lasers and Optics* V40: 9-14

Schuöcker, D, 2010. Laserschneidkopf: patent applied at Austrian patents office, 25.03.2011

Vicanek, M, Simon, G, 1987. Momentum and heat transfer of an inert gas jet to the melt in laser cutting. *Journal of Physics D. Applied Physics* Vol. 20, No. 9: 1191-1196

ACKNOWLEDGMENTS

The author is indebted to the Austrian research Promotion Agency (FFG) for funding the above work in the framework of the priority programme "Modeling and Simulating" especially to Dr. Peter Kerschl for permanent encouraging. They also acknowledge the important contribution of experimental data by Svoent Company in St. Pölten / Austria and the technical assistance of Mrs. Carina Ebli.

BIOGRAPHY

Dieter Schuöcker

1941	Born in Vienna
1968	Graduation to Dr. techn. engineering
1979-81	Voest-Alpine, Project leader for high power laser, development of laser cutting system "VALCUT"
1988	Chairman of "7th International Symposium on Gas Flow and Chemical Lasers (GCL)" in Vienna
1993	Head of the European-wide training program "EuroLaser Academy" in the framework of the COMETT and the LEONARDO initiative of the EU.
1996	Chair of nonconventional processing and laser technology of the Technical University of Vienna
2008	Foundation of the Upper Austrian Lasercenter in Gmunden / Austria

Joachim Aichinger

1980	Born in Linz
2010	Dipl.-Ing. of Mechanical Engineering
2009	Deputy head of the Upper Austrian Laser Center

Georg Schuöcker

1976	Born in Vienna
2006	Dr. techn. of mechanical engineering
2010	Svoent company, CEO