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Dynamic Phenomena in Laser Cutting and Cut Quality

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Abstract. The quality obtained with laser cutting, one of the most important processes of laser machining, is characterized by a nearly periodic pattern of striations that cause a certain roughness of the cut surfaces. Improvements of the cut quality, that would be of major technical importance, can only be obtained if the mechanism that leads to the formation of these striations is entirely understood.
The present author has argued already in 1984 that temporal fluctuations of laser power can induce oscillations of the liquid layer formed at the momentary end of the cut and its temperature, thus causing distortions of the cut surfaces due to the movement of that layer in cutting direction.
The numerical evaluation of the theoretical model yields satisfactory agreement of the "wavelength" of the striations and their dependance on the thickness of the workpiece with experimental values. So far, no attempt has been made to calculate not only the wavelength but also the depth of these striations.
It is the purpose of this paper to determine the depth of the striations and to compare the numerical values with the experimental situation. Moreover, the paper is devoted to the explanation of the fact that the laser cut surfaces are showing not only one but usually two different striation patterns, one with a finer structure adjacent to the upper surface and one with a coarser pattern adjacent to the lower surface of the workpiece.

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Laser material processing, that means drilling, cutting, welding and hardening with highly focused high-power laser beams exhibits several important advantages as, for instance, high processing speed. Therefore, laser material processing is world wide subject to a strong interest.
Laser cutting has by now reached the highest degree of maturity, and is thus used to a strongly increasing amount, although it suffers from the severe disadvantage, that the cut surfaces show a certain roughness caused by a nearly periodic pattern of more or less vertical striations. In order to improve cut quality by reducing the roughness caused by these striations, the mechanism of the formation of these distortions has to be entirely understood. Although there exist, since a long time, several different explanations for that dynamic effect, no mathematical model, that gives a deeper insight into the dynamic behavior of laser cutting and into the formation of periodic striations has been available in the near past. Just in 1984 this author presented at the 5th GCL in Oxford a first attempt to describe dynamic effects in laser cutting [1]. Based on that analytic treatment it came out that the liquid layer formed at the momentary end of the kerf [2] can carry out periodic oscillations of its width and temperature, either by resonance with fluctuations of laser power or reactive gas flow or even without any driving force due to an unstable situation in the molten layer. The critical frequency is in the order of magnitude of some 100 cycles/s. If the movement of the liquid layer in cutting direction is considered, the oscillation of the liquid layer causes a periodic distortion of the cut

surfaces. That idea has also been supported by Beyer et al. [3]. At the "Laser 85" meeting in Munich, Simon et al. presented independently obtained calculations that confirmed the above model [4].

At the same occasion the present author gave a more detailed analysis of the formation of periodic striations, that yielded a strong dependence of the striation geometry and thus cut quality on the thickness of the molten layer and the cutting speed [5], leading to the conclusion, that theoretically the formation of striations can be precluded by an appropriate adjustment of the relevant parameters as, for instance, the cutting speed.

At the present stage of the model only the wavelength of the striations has been precisely calculated, but not the depth of the striations that is most important for the determination of the roughness of the cut edges. Furtheron, no attempt has been made to explain the experimental fact that the cut edges carry actually not only one striation pattern but two, one adjacent to the upper surface of the workpiece with relatively fine pattern and the second adjacent to the lower surface of the workpiece with a relatively coarse pattern, both separated by a straight line in parallel to the surfaces of the workpiece. It is the purpose of this paper to extend the model as it existed before to a clarification of the points mentioned above.

1. Steady-State Description

It has been shown previously [6] that the liquid layer, formed at the nearly vertical momentary end of the cut, plays a most important role in laser cutting, since it converts radiation and reaction energy to heating of the workpiece and carries out material removal by evaporation from its surface and by ejection of liquid material at the lower surface of the workpiece due to the friction between the reactive gas flow and the surface of the melt.

Thus obviously modeling of laser cutting must start with the analysis of that molten layer.

It has been shown earlier [7], that this can be done by the help of several balance equations, as for the number of reactive and pure metal particles in the melt, the momentum, the energy and the mass of the molten layer. That analysis yields to final equations, namely the energy balance and the mass balance:

The energy balance contains gain by absorbed radiation a. P_L (P_L: laser power) and by reaction P_R. The latter has been shown [7] to exhibit a maximum P_{RM} for an optimum strength of the reactive gas flow. That maximum value is proportional to the cutting speed, since the maximum energy gain is obtained if all metall atoms entering the liquid layer due to the movement in the cutting direction are burned [8] (d: thickness of the workpiece, b: width of the cut, ε_R: reaction energy, n: density of the metal atoms, v: cutting speed)

$$P_{RM} = \varepsilon_R d b n_0 v \,. \qquad (1)$$

Therefore, it is assumed in the following that the gas flow is always adjusted to its optimum value, thus simplifying things considerably. On the other hand, the energy balance contains also energy loss by several mechanisms as heat conduction, evaporation, convection and melting of solid material during the movement of the liquid layer in the cutting direction. Cooling by convection is included in the optimum reaction gain given by (1) and melting can be neglected, as shown earlier [7].

So the energy balance can be written as

$$a P_L + \varepsilon_R b d n_0 v - P_{\text{loss}}(T, v) = 0 \,. \qquad (2)$$

The energy loss P_{loss} does not depend on the thickness of the molten layer s, as shown before [5], but depends obviously strongly on the temperature of the molten layer T and cutting speed v.

The mass balance contains, on one hand, mass gain by melting of solid material caused by the movement of the molten layer in cutting direction, obviously dependent on the cutting speed v. On the other hand, it contains mass loss due to evaporation and friction between the melt and the reactive gas flow, the first depending on the temperature of the melt and the second depending on the thickness of the molten layer s (m_{loss}, m_{gain}: mass loss and gain per unit time of the molten layer, respectively)

$$m_{\text{gain}}(v) - m_{\text{loss}}(T, s) = 0 \,. \qquad (3)$$

In detail, the terms appearing in (2, 3) have been given in [7]. So far, it has been assumed that the energy balance and the mass balance are simultaneously in equilibrium, that means that gain and loss terms of each balance are equal. Such an equilibrium applies to the case of cutting with a stationary molten layer. It has been shown most recently [5] that cutting with a stationary molten layer can be obtained only in a certain range of cutting speed. Outside of that range no stationary state of the liquid layer can be maintained, but that does not necessarely mean that no cutting is possible.

2. Dynamic Description

In order to consider dynamic phenomena the idea of equilibrium balances must be abandoned completely [1]. If, for instance, the energy gain exceeds all energy losses, the temperature of the liquid layer must rise. Similarly, a difference between mass gain and loss of the liquid layer causes a rise of the mass of the melt or,

in other terms, of its volume or more precisely of the thickness of the molten layer. Thus the energy balance and the mass balance become differential equations under dynamic conditions and can then be used to describe time-dependent phenomena caused, for instance, by time-dependent laser power $P_L(t)$ or reaction energy $P_R(t)$ deviating from the constant optimum value due to fluctuations in the strength of the gas flow as caused by the formation of turbulences [10].
These differential equations look as follows (c_v: specific heat of the melt per unit volume, ϱ_m: density of the molten metal). Dynamic energy balance

$$aP_L(t)+P_R(t)-P_{\text{loss}}(T,v)=c_v dbs\frac{dT}{dt}+c_v dbT\frac{ds}{dt}. \tag{4}$$

Dynamic mass balance

$$m_{\text{gain}}(v)-m_{\text{loss}}(T,s)=\varrho_m db\cdot\frac{ds}{dt}. \tag{5}$$

Although the cutting speed can be dependent on time, for instance, due to a ripple of the coordinate table moving the workpiece with respect to the laser beam, it should be assumed in the following that the latter quantity remains entirely constant. An analysis considering time-dependent cutting speed will be presented elsewhere.

3. Small Perturbation Treatment

Eqs. (4, 5) allow the calculation of the time dependence of temperature and thickness of the molten layer. They are essentially nonlinear and so the treatment can be simplified considerably by using a small perturbation approximation yielding linear equations [1].
It is thus assumed that the temperature T and the thickness s of the molten layer exhibit the following time dependance (T_0 and s_0 constant in time):

$$T(t)=T_0+T_1(t),\ T_1\ll T_0, \tag{6}$$

$$s(t)=s_0+s_1(t),\ s_1\ll s_0. \tag{7}$$

The same shall hold for $a\cdot P_L(t)$, $P_R(t)$, and $T(t)$. Accordingly, the following linearized equations are obtained

$$c_v dbs_0\frac{dT_1}{dt}+\left(\frac{\partial P_{\text{loss}}}{\partial t}\right)_0 T_1+c_v dbT_0\frac{ds_1}{dt}=aP_{L1}+P_{R1}, \tag{8}$$

$$-\left(\frac{\partial m_{\text{loss}}}{\partial T}\right)_0 T_1-\left(\frac{\partial m_{\text{loss}}}{\partial s}\right)_0 s_1=\varrho_m db\frac{ds_1}{dt}. \tag{9}$$

By substituting T int. (8) with the help of (9) the following differential equation for $s(t)$ is obtained

$$s_1''+\alpha s_1'+\omega_0^2 s_1=[aP_{L1}(t)+P_{R1}(t)]\left(\frac{\partial m_{\text{loss}}}{\partial T}\right)_0\frac{1}{c_v dbs_0\varrho_m db}, \tag{10}$$

$$\alpha=\left(\frac{\partial P_{\text{loss}}}{\partial T}\right)_0\frac{1}{c_v dbs_0}+\left(\frac{\partial m_{\text{loss}}}{\partial s}\right)\frac{1}{\varrho_m db}-\frac{T_0}{s_0}\left(\frac{\partial m_{\text{loss}}}{\partial T}\right)\frac{1}{\varrho_m db}, \tag{11}$$

$$\omega_0^2=\left(\frac{\partial P_{\text{loss}}}{\partial T}\right)_0\left(\frac{\partial m_{\text{loss}}}{\partial s}\right)_0\frac{1}{c_v dbs\cdot\varrho_m db}. \tag{12}$$

The quantities $(\partial P_{\text{loss}}/\partial T)_0$, $(\partial m_{\text{loss}}/\partial T)_0$ and $(\partial m_{\text{loss}}/\partial s)_0$ have already been evaluated for reactive gas assisted laser cutting of steel with a thickness of 5 mm and a laser power of 1.2 kW for different cutting speeds (Table 1). It is quite interesting to look at the uncertainty due to the lack of data for the specific heat of steel at temperatures near the boiling point, the temperature range relevant for laser cutting. It points out that the attenuation (Fig. 2) can go through zero. In that case, even without a time dependence of the laser power or the reactive energy gain, (10) yields oscillations of the thickness and the temperature of the molten layer with the frequency ω_0 (Fig. 1). Nevertheless, this is a special case, while in the general case the absorbed laser power fluctuates, either due to periodic changes of absorption as, for instance, in the case of

Table 1. Numerical values characterizing the molten layer

P_L	d	b	s	v	T	$\frac{\partial P_{\text{loss}}}{\partial T}$	$\frac{\partial m_{\text{loss}}}{\partial T}$	$\frac{\partial m_{\text{loss}}}{\partial V}$	c_v
$[W]$	10^{-3}	10^{-3}	10^{-3}	10^{-2}	$[K]$	$[W/K]$	$[\text{kg}/s\cdot K]$	$[\text{kg}/s\cdot m^3]$	$[VAs/m^3K]$
	[m]			$[m/s]$					
			0	0.15	2850	0.723	0.844×10^{-7}	9.975×10^5	
1200	5	0.5	0.1	1.2	3300	2.98	4.138×10^{-7}	1.543×10^5	$1700\circ\varrho_m$
			0.3	2.25	3500	5.04	7.199×10^{-7}	0.905×10^5	ϱ_m

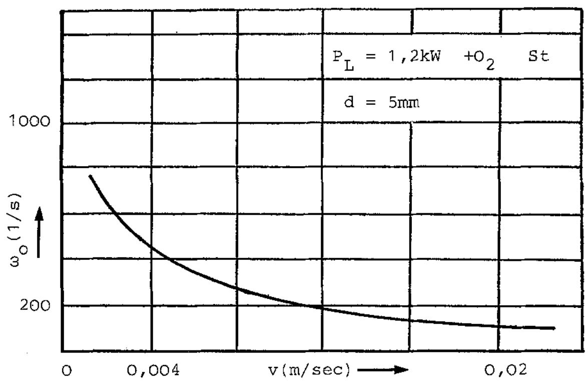

Fig. 1. Characteristic oscillation frequency of the liquid layer dependent on cutting speed

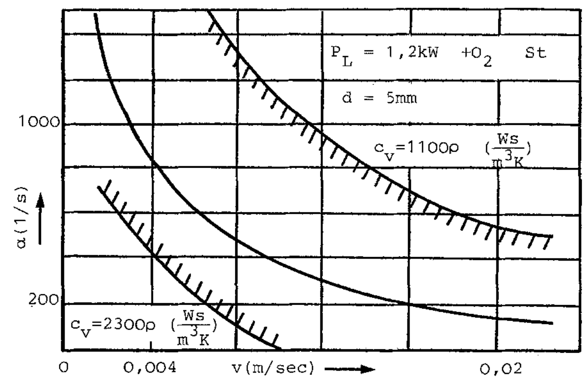

Fig. 2. Attenuation of the oscillations of the liquid layer dependent on cutting speed and uncertainty range due to the unknown specific heat

plasma formation or due to periodic distortions of the laser power itself, for instance, due to the effect of the laser radiation reflected back from the workpiece and coupled again into the laser resonator [9]. The reactive gas flow can also show periodic fluctuations due to the turbulences generated in the kerf (see below). Although, actually there will be a whole spectrum of frequences contained in the fluctuations mentioned above, for the sake of simplicity, it shall be assumed first, that the term $aP_{L1}+P_{R1}$ oscillates as a whole:

$$aP_{L1}+P_{R1}=\text{Re}\,\{\Delta_P\cdot e^{j\omega t}\}. \quad (13)$$

The solution of (10) is then obtained as

$$|s_1|^2_{\max}=\Delta_P\frac{1}{\sqrt{(\omega^2-\omega_0^2)^2+\omega^2\alpha^2}}\left(\frac{\partial m_{\text{loss}}}{\partial T}\right)_0 \cdot\frac{1}{c_v dbs_0\varrho_m db} \quad (15)$$

with

$$s_1=\text{Re}\,\{s_{1\max}\cdot e^{j\omega t}\}. \quad (14)$$

4. Formation of Striations on the Cut Surfaces

Due to the movement of the liquid layer in the cutting direction the oscillations of the latter cause a spatially periodic distortion of the cut edges.

The wavelength of that distortion has already been given in [1]:

$$\lambda_0=\frac{2\pi v}{\omega_0}. \quad (16)$$

Typical values for that quantity for reactive gas-assisted laser cutting of steel and a laser power of 1.2 kW have been given in [1] for different thicknesses of the workpiece.

The calculated rise of the wavelength with rising thickness of the workpiece agrees well with the experiment, as it shows that usually the striation patterns become more and more crude if the thickness of the workpiece is increased.

For the depth of the periodic structure formed on the cut edges, limits can be found from the following idea:

During the derivation of the dynamic mass balance, it has been assumed that the whole change of the volume due to a difference between mass gain and loss is caused by a changing thickness of the molten layer. Thus, the peak value of that volume during the oscillation of the liquid layer is (b: steady-state value of the kerf width equal to the width of the molten layer)

$$V_{1\max}=bds_{1\max}. \quad (17)$$

There is no reason why temporal changes of the volume of the liquid layer should take place only by changing the thickness of that layer. Therefore, it must be argued that also changes of the width of the molten layer can take place. If it would be assumed that the total change of volume is caused by changing of the width of the liquid layer, the maximum value of the oscillating width must have the following upper limit (s_0 steady state value of the thickness of the molten layer)

$$b_{1\max}=\frac{b}{s_0}s_{1\max}. \quad (18)$$

Obviously, the maximum depth of the structure impressed on the cut edges $h_{1\max}$ is given by

$$h_{1\max}=b_{1\max}/2. \quad (19)$$

Typical theoretical values for the wavelength and the depth of the striation pattern imposed on the cut edges are given in Figs. 3 and 4 for reactive gas-assisted laser cutting of steel with a laser power of 1.2 kW for different values of the cutting speed.

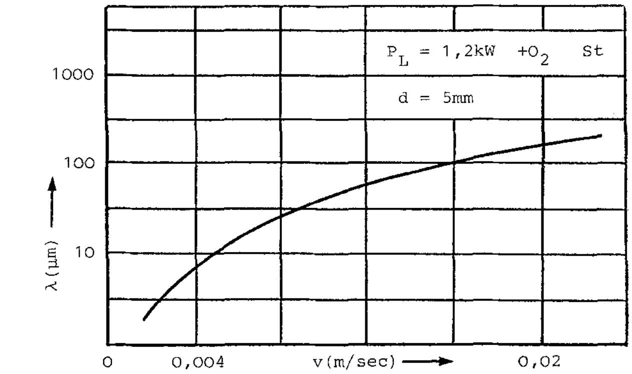

Fig. 3. Wavelength of the striations on the cut edges dependent on cutting speed

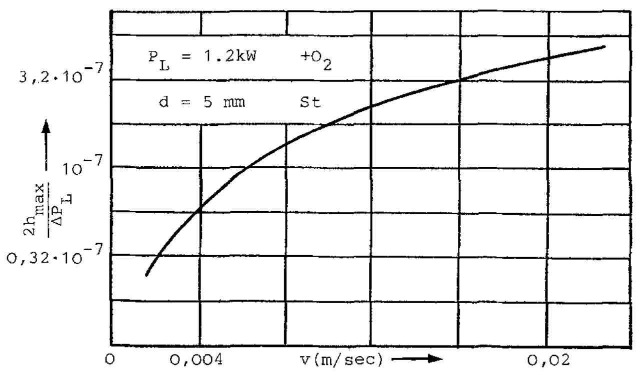

Fig. 4. Maximum depth of the striations on the cut edges dependent on cutting speed

5. Formation of a Double-Striation Pattern

Usually the edges of laser cuts show not only one single striation pattern but actually two different patterns, one near the upper surface adjacent to the cutting head with a relatively fine pattern with short wavelength and another at the lower part of the edge with a relatively coarse pattern with much longer wavelength. Both patterns are separated by a straight line extending in parallel to the surface of the workpiece. This phenomenon can be understood in terms of the formation of two separated liquid layers, one near the upper surface of the workpiece and one at the lower surface.

The critical frequency given by (12) depends on the rise of the energy loss in the liquid layer and the mass loss, both with respect to the temperature. If the temperature becomes higher, the first one increases because the evaporation increases nonlinearly and the second one increases also because the viscosity of the melt decreases, thus enhancing mass ejection by friction with the vertical gas flow. Due to that influence of the temperature on the critical frequency, the different wavelengths of the two striation patterns can be explained in terms of the higher temperature in the upper liquid layer and the lower temperature in the lower molten body. After La Rocca [10] the build up of two separated liquid layers, the upper with higher temperature and the lower with lower temperature can be explained in terms of hydrodynamics: The reactive-gas flow enters the kerf subsonic, but is heated due to the interaction with the hot liquid layer [8], the more the deeper it penetrates into the bulk of the workpiece. The density of the gas flow is accordingly reduced and thus the cut acts as a converging nozzle, raising the speed of the gas flow.

After a critical distance from the surface, the flow becomes sonic and therefore turbulent. From that point on, a second molten layer exists that shows different properties due to the interaction with the turbulent gas flow. That molten layer reaches only lower temperatures, since the laser beam reaches it already somewhat weakened by the foregoing absorption and due to the more efficient cooling by the turbulent gas flow. The oscillations of that second liquid layer can be excited by the fluctuations of the turbulent gas flow. Since the frequency of the oscillations of the liquid layer depends strongly on the temperature, as discussed above, the upper molten layer and the lower molten layer must show different oscillation frequencies:

$$\omega_{0\text{up}} = \omega(T_{\text{up}}), \tag{20}$$

and

$$\omega_{0\text{lo}} = \omega(T_{\text{lo}}). \tag{20a}$$

Since the oscillation frequency increases with rising temperature of the melt (see above) the wavelength of the upper pattern must be lower than that of the lower pattern:

$$\lambda_{0\text{up}} < \lambda_{0\text{lo}}. \tag{21}$$

It should be mentioned that both wavelengthes must be smaller than those calculated under the assumption of one single pattern, since the wavelength depends strongly on the vertical extension of the layer, the thickness of the workpiece in the case of one single layer, as shown in [1], and the latter is reduced to, say, one half due to the splitting into two layers.

Since the temperature of the lower layer is determined by hydrodynamic effects and yet unknown, no numerical results for the wavelength of the lower striations can be given up to now.

6. Conclusions

The dynamic analysis of laser cutting outlined above describes oscillations of the molten layer formed at the momentary end of the cut kerf during laser cutting.

With these oscillations, the main phenomena of the formation of a periodic structure on the cut edges, as dependance of the wavelength and the depth of the striations on the thickness of the workpiece and on the cutting speed can be explained and described analytically. Moreover, the formation of multiple patterns as usually obtained in cutting of thicker materials can be explained qualitatively.

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