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STRIATION FORMATION AND SURFACE FINISH IN LASER CUTTING OF MILD STEEL

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ABSTRACT

The mechanisms of melt ejection and striation formation in laser cutting of mild steel are discussed. It is argued that the melt ejection from the cutting front is not a steady state process, but rather shows a cyclic phenomenon. The striation are strongly affected by the unstable characteristic of the thin liquid film on the cutting front during the melt ejection, together with the oxidation and heat transfer process. Dependent on the cutting speed, the liquid film will either rupture or generate waves on the cutting front. Theoretical explanation is given according to the instability theory of a thin liquid film in a high velocity gas jet and the diffusion controlled oxidation theory. The striation frequency and depth can be estimated according to the above theories. Experimental investigations were carried out and the results are consistent with the calculations. The better understanding has shed light on further investigations and optimal process development.

NOMENCLATURE

A	constant
b	kerf width
B	constant
C	oxygen concentration
c	wave velocity
c_f	friction factor
c_p	heat capacity
D	diffusion coefficient
d	the work-piece thickness
f	wave frequency
h	liquid film thickness
I	defined in equation (11)
J	particle current in oxidation
K	heat conductivity
k	wave number
k_B	Boltzmann constant
P_r	normal stress exerted at the interface
P_g	gas pressure
p_o	the oxygen pressure at the surface of the melt
R	Reynolds number of liquid, $R = Vh/\nu$
s_m	the maximum thickness of the oxide layer
T_i	tangential stress exerted at the interface
T_0	activation temperature
t	time
t_p	time period per oxidation cycle
U	gas velocity profile
U_0	streamwise gas velocity
u	internal energy
V	interfacial velocity
v	cutting speed
v_*	friction velocity
W	activation energy
x	oxidation direction
α	$\alpha = kh$, dimensionless wave number
β	defined in equation (12)
γ	surface tension
λ	wave length
μ	viscosity of the melt
μ_g	viscosity of gas at surface temperature
ρ	density of the melt
ρ_g	density of the gas at surface temperature
σ_r	circular frequency of the harmonic oscillation
σ_i	growth rate of the harmonic oscillation
τ	mean tangential stress
ν	kinetic viscosity of the melt
ν_g	kinetic viscosity of the gas
ϕ	stream function
Π_r	dimensionless normal stress at the interface
Σ_i	dimensionless tangential stress at the interface

1. INTRODUCTION

The formation of periodic patterns (striation) has drawn much attention in CO_2 laser cutting of mild steel since it strongly affects the quality of cut finish (Fig. 1). However, the physical mechanisms of striation formation are not well understood and far from being described quantitatively. Obviously, striations are results of some non-steady nature of cutting process. Most of investigators argue that the striation patterns are due to an oscillated molten front in the course of laser cutting. There are several possible mechanisms which will result in an oscillated molten front under steady-state mechanical conditions. The fluctuation of absorbed laser power during the laser beam and the gas flow interacting with the work-piece will bring about unstable nature of the molten front (Schuocker, 1986). In special cases, the liquid layer can oscillate with a natural frequency even without absorbed power fluctuations (Schuocker, 1986). The high-speed gas jet during melt ejection will cause hydrodynamic instabilities of the molten front (Vicanek et al., 1986). However, the characteristic predictions of the striation pattern in these reports are either non-obtainable or not accurate.

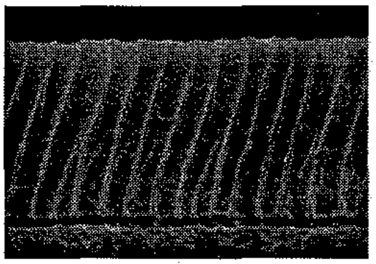

Fig. 1 typical cut edges showing striation patterns

Arata et al. (1979) first did a detailed experimental investigation about the molten front in the cutting of process. They suggested that when the cutting speeds are less than the velocity of reactive front, the ignition and extinction cyclic reaction begins to happen and they proposed a critical cutting speed of 2 m/min for mild steel of certain thickness, above which no such cycle exists. But even the cutting speed is above the critical speed and under so called the steady cutting, striations still exist. An cyclic oxidation model is further suggested (Ivarson et al., 1994). For diffusion controlled reaction, the rate of chemical reaction is time dependent, being rapid in the early stages but decreasing markedly as the thickness of the oxide layer increases. So the oxide layer will expand rapidly at first but slow down afterwards. Once the oxide is blown out from the cutting front, due to a sudden decrease of the oxide layer, another expansion will begin (Fig. 2).

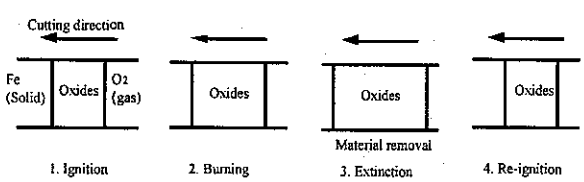

Fig. 2 The oxidation model proposed by Ivarson et al. (1994).

An instability analysis was given based on the energy balance and the simplified parabolic growth law for oxidation (Simon and Gratzke, 1989). It is clearly such an cyclic oxidation will have strong effects on the cutting edge. Heat transfer is greatly enhanced by the exothermic oxidation. But the oxides generally have less conductivity and higher melting point than the pure iron. Once the oxide layer gets thick enough, it will impede the ongoing of heat conductivity. Thus the molting front basically has the same oscillated patterns as the oxide layer. Although this model gives a quite convincing explanation on the generation of striation patterns on the cutting edge, it is still not clear that the melt is largely removed in the extinction stage. Most researchers assume that the melt removing is a continuous and steady-state process. If that is the case, then the oxidation cycle will still not generate, because finally when the oxidation and melting speed is the same as the melt removing rate, the whole process will become steady-state.

The mechanism of the melt removal is investigated in this paper and it is shown that there are unsteady characteristics in the removal process. A typical profile of laser cutting of mild steel is sketched in Fig. 3. Under normal cutting conditions, waves are generated on the molten front which will give a sudden increase of melt removal. The details of wave generation and its influence on striation formation will be discussed in next two sections.

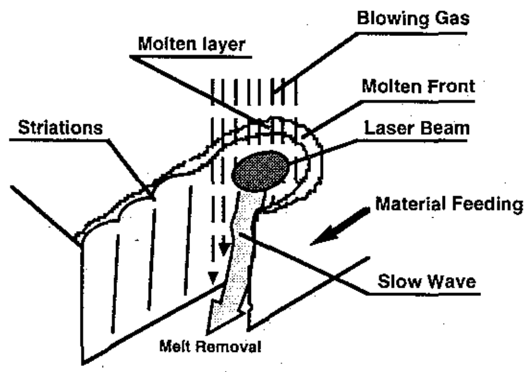

Fig. 3 Schematical drawing of oxygen cutting of mild steel

2. PHYSICAL MODEL OF MELT REMOVAL AND STRIATION FORMATION

The phenomena of a thin liquid film under the gas flow have been studied over decades (Hanratty, 1983; Lin, 1983). The instability behavior of the liquid film is largely dependent on the gas velocity, the liquid flow rate (or Reynolds number) and the film thickness. Consider a thick liquid layer under a high-velocity gas, ripples will generate on the surface because the viscous dissipation is less than the energy transferred by the wave-induced pressure perturbation. The wave behaviors depend on the gas velocity and the liquid flow rate. If we reduce the film thickness, the surface will smooth out because the friction in the liquid phase can overcome the pressure perturbation. However, if we further reduce the film thickness to a very small value, it is found out that the liquid film is unstable because the wave-induced shear stress perturbation is sufficient to overcome the restoring forces, and there are so called slow waves generated on the surface (Craik, 1966). The amplitude of the slow wave can be comparable to the film thickness. A common sense is that, if the liquid film gets further thin enough and has less flow rate, the film will rupture. In addition to aforementioned destabilizing forces, the intermolecular dispersion forces may become important in the film rupture.

For the cases of the laser cutting of mild steel, it is commonly accepted that the molten front thickness has the order of 10^{-5}m (Arata et al., 1979; Vicanek et al., 1986; Makashev, 1993). For the liquid film as thin as the molten front, the film is unstable and can easily rupture. (It will be shown later that the critical thickness for slow waves is above the molten front thickness).

Consider the top part of the molten front. At low cutting speeds, the liquid film has relatively long exposure time in the gas flow and usually, the liquid film will rupture since there is not enough liquid flow rate on the top part of the molten front. This phenomenon has been observed and described by Arata et al. (1979). When the cutting speed increases, the period for film rupture becomes shorter. At some critical cutting speed, there is not enough time for instabilities to develop to cause film rupture, and there is always a liquid film on the top of the molten front. This was described by Arata et al. (1979) as steady cutting, which corresponds to a cutting speed of 2m/min. However, this thin liquid film is still unstable, instead of film rupture, slow waves will generate. Once the crest of the slow wave moves downwards from the top of the molten front, much more melt is removed and the oxidation coupled with the heat conduction begins to expand. The process is fast at first and slows down until another wave crest is coming and moving downwards. Thus a expansion-compression cyclic pattern is still formed (Fig. 4).

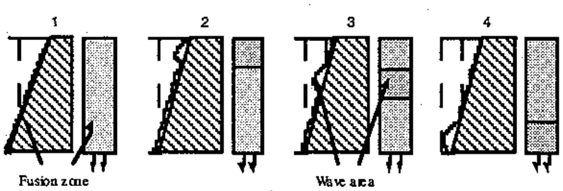

Fig. 4 Schematic illustration of the molten front at high cutting speeds

It has been shown by Makashev et al. (1993) that a steady flow of the melt layer on the upper edge is impossible. However, instead of wave generation. they proposed that a melt drop will quickly grow up to a critical size then moving down. It is unreasonable to produce the droplets on the upper edge, because the liquid flow rate is very small and the liquid layer is basically in the laminar state. Moreover, as mentioned earlier, there is not enough time for film rupture in the steady cutting. Vicanek et al. (1986) treated the melt flow as a two-dimensional boundary layer and gave the stationary thickness of the molten layer. Also instability analysis was presented. However, the stress perturbation was not considered in their approach and hence the results are not accurate to give a quantitative description of the striation pattern.

The melting (or oxidation) and melt ejection are essentially coupled each other to present a cyclic pattern of the molten front. The oscillation frequency of the molten front is related with the wave frequency on the molten front, which is dependent upon the momentum and energy balance of the gas flow and the liquid phase.

3. THEORETICAL BACKGROUND

3.1 Instabilities of the Cutting Front

Generally, the molten layer is an inhomogeneous, non-Newtonian fluid accompanied with large temperature gradient and phase change. Thus, it is highly difficult to describe the motion of the molten layer. Most researchers assume it is Newtonian, homogeneous and this assumption is accepted here so that the normal instability analysis is applicable.

The stream function representing a single oscillation of the disturbance is assumed to be of the form

$$\phi (x, y, t) = -\phi (y)\, e^{i(kx-\sigma t)} \qquad (1)$$

where k is the wave number and $\lambda = 2\pi/k$ is the wave length. The quantity σ is complex,

$$\sigma = \sigma_r + i\sigma_i \qquad (2)$$

where σ_r is the circular frequency of the partial oscillation, and σ_i is the growth rate which determines the degree of amplification or damping.

If we write the perturbation velocities as the derivatives of the stream function and substitute them into the linearized Navire-Stokes equation, we will finally obtain the so called Orr-Sommerfeld equation. The instability analysis is essentially to solve an eigenvalue problem of Orr-Sommerfeld equation with the kinetic and kinematics boundary conditions at the interface and the wall. The results of Craik's analysis (1966) is directly cited here for convenience.

Instability occurs when the surface stress is sufficient to overcome the restoring forces of surface tension. The following equation can be achieved (Craik, 1966):

$$P_r + (3T_i/2kh) \geq \gamma k^2 h \qquad (3)$$

where P_r and T_i are normal and tangential stress exerted at the interface, k the wave number, γ the surface tension and h is the thickness of the liquid film The condition for the derivation of the above equation is that (kh)R is enough small, where R is the liquid Reynolds number. This condition is satisfied for the case of laser cutting. When the liquid film is so thin that the intermolecular interaction becomes important, the effect can be included by taking into a dispersion force term on the left side of the equation. Thus the instability analyses of the film rupture and slow wave basically take the same form of the characteristic equation. For simplicity, we only consider the slow waves under the steady cutting conditions.

In the case of small film thickness, the shear force perturbation will be dominant, the Eq. (3) can be further simplified as:

$$h < (3T_i/2\gamma k^3)^{1/2} \qquad (4)$$

The critical thickness for stability can be evaluated for a given wave length, if the shear stress perturbation can be accordingly calculated. Most theoretical analyses of the interfacial instabilities have adopted Benjamin's quasi-laminar estimate (Craik, 1966). A more accurate approach is given by (Hanratty, 1983) which takes into account of turbulent effects, but involves much more mathematics. Benjamin's method is expected to give correct orders of the results under certain range of validity (Craik, 1966) and is used here to evaluate the scaling of the surface stress and critical film thickness for instability.

The surface stress can be evaluated as

$$T_i = (\rho V^2)\Sigma_i \qquad (5)$$
$$\Sigma_i = (\beta I/c_f)(\alpha)^3(\alpha R)^{-4/3} \qquad (6)$$

and

$$P_r = (\rho V^2)\Pi_r \qquad (7)$$
$$\Pi_r = \alpha I/R\ c_f \qquad (8)$$

where ρ is the melt density, α = kh, the dimensionless wave number, ν the kinetic viscosity of the melt, c_f the friction factor and V is the interfacial velocity. R is the Reynolds number of the liquid, R= Vh/ν. The expressions for I and β are (Craik, 1966)

$$I = \int_0^\infty (U(y)/U_0)^2 e^{-\alpha y}\, d(\alpha y) \qquad (9)$$
$$\beta = 1.188\,(\nu_g/\nu)^{2/3}(\rho_g/\rho) \qquad (10)$$

where U(y) and U_0 are gas velocity profiles and the streamwise gas velocity. ν_g and ν are kinetic viscosity of the gas and the melt respectively. ρ_g is the gas density. c_f can be calculated according to

$$\mu V/h = c_f \rho_g U_0^2 \qquad (11)$$

where μ is the viscosity of the melt.

The interfacial velocity can be calculated using 1/7th power law of mean velocity profile (Schlichting, 1979), that is

$$U_0/v_* = 8.74(b v_*/2\nu_g)^{1/7} \qquad (12)$$
$$\rho_g\, v_*^2 = \mu V/h \qquad (13)$$

where b is the kerf width, ν_g the kinetic viscosity of the gas and v_* is the friction velocity. The properties of the gas phase should be taken at the local temperature.

The critical thickness below which instabilities occurs is found to be approximately 5.6×10^{-4}m if the parameters in Table 1 are used. The wave number k is evaluated as k = $2\pi f/V$, where f is the striation frequency. The calculated critical thickness is about one order larger then the film thickness on the molten front. Thus the molten front is unstable.

Table 1: Physical Quantities and Parameters Used in the Calculation:

U_0 = 340 m/s	$\mu_g = 4.5\times10^{-5}$ kg/(ms)
b = 0.4×10^{-3} m	$\rho = 7.8\times10^3$ kg/m^3
f = 230 s^{-1}	ρ_g = 0.23 kg/m^3
γ = 1.0 kg/s^2	$\nu = 0.64\times10^{-6}$ m^2/s
$\mu = 5\times10^{-3}$ kg/(ms)	$\nu_g = 2.25\times10^{-4}$ m^2/s

3.2 Prediction of Striation Frequency

According to aforementioned physical model, the striation frequency is equivalent to the oscillation frequency of melt ejection and oxidation. Under the steady cutting conditions, the frequency should be equivalent to the slow wave frequency. The wave number of the slow wave is approximated to be at the critical wave number where the mean tangential stress τ attain the minimum value to sustain undamped disturbances for the liquid film of thickness h. The dimensional form of Eq. (3) is

$$I/c_f[k\tau/\rho + 3\beta\nu^{2/3}(k\tau/\rho)/(2h)] = \gamma k^2/\rho \quad (14)$$

Taking derivative of $\partial\tau/\partial k$ from the above equation will give the positive critical wave number (Craik, 1966)

$$k = (I/c_f)\tau/4\gamma \qquad (15)$$

The mean tangential stress can be evaluated according to Vicanek et al. (1986) which takes into account of the metal section thickness.

$$\tau = (\rho_g \mu_g U_0^3/d)^{1/2} \qquad (16)$$

Theoretically, for a given wave number, the wave growth rate and wave frequency can be calculated from the characteristic equation. However, approximations can be made to avoid complications of solving the whole characteristic equation. Both theoretical and experimental results show that the wave velocity is slightly less than the interfacial velocity. A good approximation is just putting a coefficient of 0.8 (Craik, 1966).

$$c = 0.8V \qquad (17)$$

where c is the wave velocity and V is the interfacial velocity. This takes into account of the non-linear effects which may reduce the wave velocity. Thus we can use V from Eq. (12) and Eq. (13) to approximate wave velocity. The striation frequency and wavelength will be

$$f = 0.8Vk/2\pi \qquad (18)$$

$$\lambda = v/f \qquad (19)$$

Here v is the cutting speed. V is dependent on the stationary liquid film thickness h, which should be derived from steady state energy and momentum balance. The calculation method from Vicanek et al. (1986) is used to give the values of film thickness h with the varying cutting speed and the gas velocity. They treated the molten front to be a plane and solved the momentum equations based on boundary theory, taking the physical properties at the wall temperature instead of solving the energy equation.

3.3 Prediction of Striation Depth

It is difficult to evaluate the expansion of the oxidation and the melting in each cycle to give a quantitative estimate of the striation roughness. Assume that melting and oxidation have linear relationship. This is reasonable because the heat conduction and oxidation take the same parabolic forms as

$$\partial C/\partial t = \partial/\partial x\ (D\partial C/\partial x) \qquad (20)$$

$$\rho c_p \partial T/\partial t = \partial/\partial x\ (K\partial T/\partial x) \qquad (21)$$

where C is the oxygen concentration, ρc_p the density-heat capacity product, D and K are diffusion coefficient and heat conductivity and x is the oxidation direction. The oxidation process occurs at a specific film thickness which is dependent upon the temperature and oxygen pressure in the system. The diffusion controlled oxidation process can be described as

$$ds/dt = BJ = BD\partial C/\partial x \qquad (22)$$

where s is the oxide layer thickness, J the particle current and B is a constant. If the quasi steady state approximation is valid that the concentration on oxide surface is independent of the oxide film, then Eq. (22) can be written as

$$ds/dt = BD(C_o\text{-}C_s)/s(t) \approx BDC_o/s(t) \qquad (23)$$

where subscripts s denotes the interface of metal and oxide and o is the interface of oxide and oxygen. The temperature dependence of diffusion coefficient is due to an exponential factor containing an activation energy W and Boltzmann constant k_B

$$D \propto \exp(-W/k_BT) \qquad (24)$$

Also C_o is temperature dependent.

$$C_o \propto \exp(-u/k_BT) \qquad (25)$$

where u is the internal energy. We can write the oxidation equation as

$$ds/dt = A(p_o)\exp(-T_0/T)/s(t) \qquad (26)$$

where A is a coefficient which is has presumably linear relation with the oxygen pressure p_o at the surface of the molten front. T_0 is the activation temperature for the diffusion. The transient temperature is dependent on local energy balance. However, a rough estimate can be achieved by neglecting temperature variation and simply integrating Eq. (26) to give the parabolic equation:

$$s_m^2 = A(p_o)\ t_p \qquad (27)$$

where s_m is the maximum thickness of the oxide layer. The time period t_p is the inverse of frequency from Eq. (18). The equation can be used to predict the maximum depth of the striations based on calibration.

4. CACULATIONALAND EXPERIMENTAL RESULTS

For a given power of laser, the striation frequency is related to the surface velocity (Eq. (13)) and wave number (Eq. (15)) which depend on the gas velocity and the liquid film thickness. The liquid film thickness is dependent on the gas velocity and the cutting speed.

Experiments were carried out of oxygen cutting of 1.6 mm thick steel 1018 with CO_2 laser. In the first group of cutting, the gas pressure is held at 2.1 bar (30 psi, measured on gauge) and the cutting speed varied from 15 mm/s to 50 mm/s. In the second group of cutting, the cutting speed is fixed at 30 mm/s and the gas pressure varied from 0.8 to 3.8 bar (measured on gauge). (See Table 2). The striation wavelength and depth are obtained from Talysurf profiles taken from the position 0.5 mm from the top of the cut edge.

Table 2: Experimental Conditions

Group 1	Group 2
Thickness 1.6 mm Power 500 W gas pressure 2.1 bar cut speed 15-50 mm/s	Thickness 1.6 mm Power 500 W gas pressure 0.8-3.8 bar cut speed 30 mm/s

Figure 5, 6 show the calculated liquid film thickness and interfacial velocity against the cutting speed, corresponding to the experimental parameters. The wave number calculated from Eq. (15) is nearly constant against the cutting speed. The corresponding wavelength of slow waves is about 1.56 mm if a typical value of $I = 0.15$ in Eq. (9) is chosen.

The predicted striation wavelength and the experimental results are given in Fig. 7. Though there are many factors which are difficult to be evaluate accurately, the predicted striation wavelengths basically agree with the experimental results. The increase of the cutting speed will increase the liquid film thickness and thus increase the interfacial velocity to give a rise of striation frequency, but not as much as the increase of the cutting speed. Therefore, the striation wavelengths will increase as the cutting speed increases.

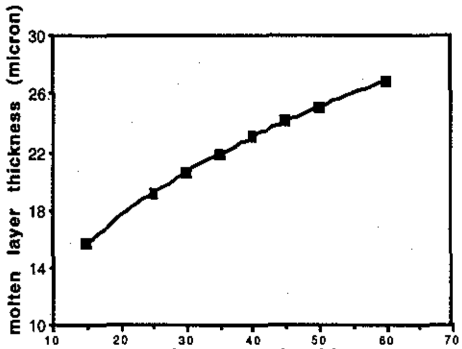

Fig. 5 the calculated liquid film thickness versus cutting speed

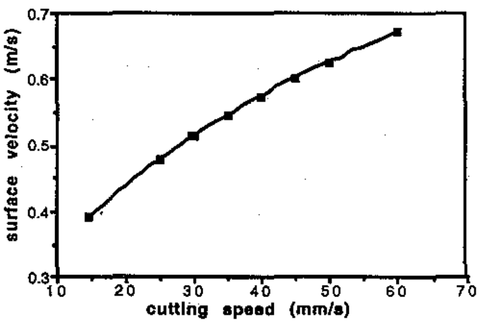

Fig. 6 the calculated interfacial velocity versus cutting speed

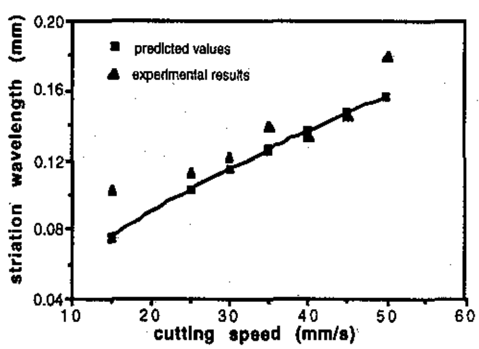

Fig. 7 striation wavelength versus cutting speed

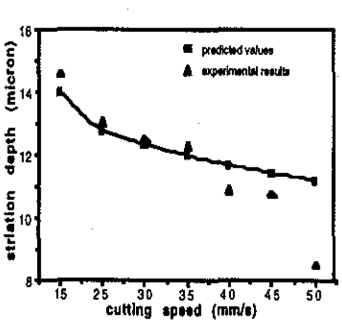

Fig. 8 maximum striation depth versus cutting speed

Figure 8 shows the predicted maximum striation depth against the experimental measurements. The coefficient in Eq. (27) is calibrated to be a constant of 4×10^{-8}. The increase of the oscillation frequency by increasing the cutting speed will give a shorter time period for the oxidation and the melting process, thus reduce the striation depth. The prediction is consistent with the experimental results.

For convergent nozzles, when the stagnant gas pressure is higher than 0.89 bar (measured on gauge), that is, when the ambient pressure is lower than the critical pressure (0.528 of stagnant gas pressure), the gas jet can not expands normally. The gas pressure at the nozzle exit will be hold at the critical pressure (choked flow) and the velocity is equivalent to the sound velocity at the local temperature. Immediately after the nozzle exit, there is a system of shockwaves beginning at the nozzle edge (Fieret, 1987). However, since the top part of the work-piece is very close to the nozzle exit (0.3-1.5 mm, usually within the first Mach shock disk (Fieret, 1987)), the local pressure can be approximated as the critical pressure and the velocity is nearly a constant. Since most of cutting cases occur at a gas pressure higher than 0.89 bar, the gas velocity at the nozzle exit will keep as the sound velocity. Consequently, the wave velocity will not change and the striation frequency is almost independent of the gas pressure. Figure 9 shows the measured striation wavelength against the gas pressure. The wavelength does not change much when the gas pressure is higher than 0.89 bar.

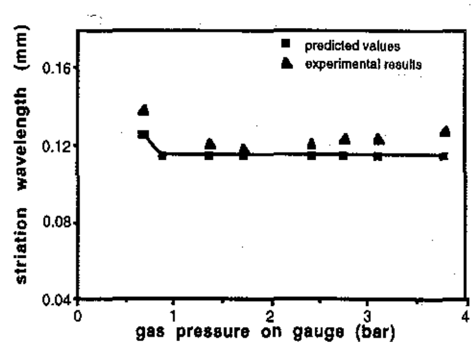

Fig. 9 striation wavelength versus gas pressure

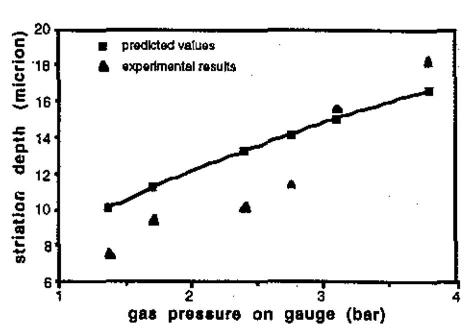

Fig. 10 maximum striation depth versus gas pressure

Figure 10 shows the maximum striation depth against the gas pressure. The p_0 in Eq. (27) is the stagnant pressure on the cut edge, which is nearly equal to the critical pressure at the nozzle exit plus the velocity head. The pressure on the cut edge increases as the gas pressure increases, resulting in higher oxygen concentrations on the cut edge, which is beneficial for oxidation. Thus the striation depth will increase.

In reality, a slow wave on the molten front may consist of a band of wave numbers and the wave numbers may be away from the critical wave number. It is interesting to note that when thick sections are cut, there are two striation patterns produced on cut edges with the primary striation pattern on the top and another irregular pattern on the bottom. This is understandable if there are two waves on the cut edge which correlate to two striation patterns. The transition for two striation patterns occurs at the thickness about 1.5 mm to 2.0 mm. This is close to the calculated value of wavelength. When waves travel downwards, the wave velocities become irregular, causing relatively irregular of the secondary striation pattern. This topic is intended to be investigated in the future work.

In the current calculation, the physical properties of gas and liquid phase are assumed to be constant. The approximation is valid only when the energy balance does not change much as the cutting speed or the gas pressure varies. A more accurate model would incorporate the energy balance into the calculations. Since the oxidation process in laser cutting is far from being well understood and the relationship between the molten layer and the oxidation layer is not clear, some approximations were made and the calculations have to be calibrated. The molten front is simplified to be two-dimensional, of uniform thickness. The actual profile of the molten front is however curved and the thickness increases from top to bottom.

There are other effects which may have influences on the instabilities of the thin liquid film. There are shock waves in the gas jet after the nozzle exit and the gas jet becomes turbulent because the reservoir pressure for laser cutting is usually higher than 0.89 bar of gauge pressure. The turbulent fluctuation of the airflow will increase the surface stresses produced by interaction of the mean airflow, making the liquid film more unstable. The high temperature gas has higher viscosity which is subject to instability. The viscosity and the surface tension of the liquid phase generally have stabilizing effects on the liquid film. In oxidation cutting, the viscosity and the surface tension of the iron oxide are lower than those of pure molten iron, which make the molten front more unstable.

5. CONCLUSION

A theory of the unstable characteristic of the melt ejection combined with the oxidation oscillation is proposed to explain the mechanism of the striation generation. When the cutting speed is small, the liquid film will rupture on the cutting front. When the cutting speed is increased to some point, slow waves are produced on the top of the cutting front instead of film rupture. Each of the wave crest or film rupture will result in a sudden increase of the melt removal and thus the acceleration of the oxidation and the melting. Thus a cyclic pattern is formed which will generate striations on the cut edge. The striation frequency is related to the frequency of the slow waves or film rupture. The calculated striation frequency (or wavelength) matches the experimental results well. The calculated frequency can be used to evaluate the time period of each oxidation cycle. The maximum depth of the striation pattern is predicted after some approximations are made. The predicted tendencies are consistent with the experimental results.

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