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A NEW TECHNIQUE TO CHARACTERIZE AND PREDICT LASER CUT STRIATIONS

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Abstract—The quality of a laser-made cut is of the utmost importance in laser processing. Any improvement in this area would be of considerable significance, in that it would lead to an elimination of post-machining operations. Currently the mechanisms governing the laser cutting process are not fully understood, partially due to the fact that laser cutting is a highly complex thermal process. It is the aim of the authors therefore to critically investigate the dynamic phenomena occurring within the cutting front, viz. the formation of striations, and the effect they have on the resulting cutting quality. A new technique for determining the frequency of the striations formed and the depth of the periodic structure has been developed. This is the first real attempt at accurately determining this most important quality index, surface roughness. Auxiliary information such as kerf width can also be ascertained. This leads to a more complete characterization of laser cutting quality. Results have shown that both quality indices correlate well with those actually obtained. The conceptual model developed supports the sideways burning theory for the formation of striations. It is argued that more than one mechanism for stria formation could exist and, as cutting conditions change, a move from one predominant mechanism to another could occur. This technique can be used in conjunction with theoretical models undertaken previously, whereby prediction of expected cut quality prior to machine operation will be possible. This has the ability of reducing set-up times involving parameter tuning, and leads to an optimized starting solution. The feasibility of detecting striation frequency on-line is currently being assessed through different sensing techniques. This will result in direct real-time surface roughness prediction and monitoring. Results will be published shortly.

NOMENCLATURE

a	thermal diffusivity
$aP_L(t)$	absorbed laser power
a_t	white noise
b	width of the cut
c_v	specific heat of the melt per unit volume
d	plate thickness
D_i	dispersion percentage
f_n	frequency corresponding to a pair of complex conjugate eigenvalues
k	thermal conductivity
K_0	Bessel function, 2nd kind and zero order
m	moving average order
$m_{gain}(v)$	mass gain per unit time of the molten layer
$m_{loss}(T,s)$	mass loss per unit time of the molten layer
N	number of observations
n	autoregressive order
$P_R(t)$	reaction energy
$P_{loss}(T,v)$	energy loss
Q	heat input/unit time
Q_m	density of the molten metal
R	distance from the heat source = $\sqrt{(x2 + y2)}$
R_t	maximum roughness height
R_a	arithmetical average roughness
s	thickness of the molten layer
t	time
T	temperature at point x, y
T_o	original plate temperature
v	processing speed
w	oscillation frequency of $aP_{L1} + P_{R1}$
w_o	oscillation frequency of the thickness and temperature of the molten layer
X_t	discrete series of observations

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δ	striation wavelength
ϕ	autoregressive parameter
θ	moving average parameter
Δp	oscillation size of $aP_{L1} + P_{R1}$
λ_i	eigenvalue

1. INTRODUCTION

Laser cutting has made significant headway into the well established area of metal cutting, and has done so for a number of reasons. These are well documented. Amongst these reasons, is the ability of lasers to produce high quality cuts at reasonable production rates. Laser cutting has become automated in the same way as many other processes, due to the explosion in the availability of computer technology. "Since the capital and operating costs for laser systems are large, high material removal rates, high dimensional accuracy, good surface quality and a high degree of repeatability must be achieved to make these processes economically viable" [1].

There have been numerous research efforts undertaken previously in order to understand and hence improve laser cutting quality [2]. In particular, the formation of striations has received much attention because it has been shown to strongly affect the quality of laser cutting. Striations appear on the cut edge as relatively regular straight lines which run at often slight angles to the laser beam axis, when reasonable laser parameters are selected. A more complex pattern is observable when such parameters are incorrectly determined and poor quality cutting often occurs as a result. There have existed for a long time, several different explanations for stria occurrence, but there is still no general consensus on this dynamic effect.

Many explanations have been prone to criticism because they are purely qualitative in nature, and only postulate on likely causes for the appearance of this periodic structure. Without any mathematical model by which results can be compared, many of these are strongly challenged. There have been two explanations, though, which have stood head and shoulders above the rest.

It has been shown by Schuocker that pulsations in the molten layer prior to it being blown out of the kerf, cause periodic striations to form. It was suggested that fluctuations in both absorbed laser power and reactive gas flow could cause both the thickness and temperature of the liquid layer to oscillate. Absorbed power fluctuations can be caused by periodic laser beam variations or material absorptivity variations. Reaction energy fluctuations can be caused by oscillations in the strength of the gas flow due to turbulences generated in the kerf. It was also shown that in special cases, even without such fluctuations occurring, the liquid layer can oscillate with a natural frequency [3–7].

The results obtained with these models for the natural frequency have correlated very well with experimental investigations undertaken. The model was also the first theoretical attempt at calculating the depth of these striations, but only reasonable order of magnitude values are obtainable. Although the model accurately determines the frequency of this oscillation and presents a strong explanation for why such surface ripples occur, it is clearly limited in its use for characterizing and predicting surface roughness or striation depth, which has been recognized as a very important quality index in laser cutting. This mechanism will be referred to as the liquid layer oscillation theory.

Arata has given another explanation for this phenomenon. He suggests that at cutting speeds less than the speed of the reaction front (caused by oxidation), sideways burning occurs and results in the periodic forming of a stria [8]. This effect was observed using high speed photography techniques. Although this famous work was capable of providing a very convincing explanation for such ocurrence, it suffered from being qualitative in nature. This theory will be referred to as the sideways burning theory.

Babenko has shown previously that by use of the solution of the moving line source, the kerf width can be given as the maximum lateral extension of the melting isotherm [9]. This will be explained later in greater detail. Results showed good correlation to theoretically determined values.

It is the aim of the present authors therefore to extend the previous work of Babenko, in order to develop a means of characterizing and predicting surface roughness. This will be the first real attempt at accurately undertaking such a task. In order to do this, though, striation frequency or wavelength needs to be accurately modeled. The sideways burning theory will also be quantified as a result of this work. Mechanisms causing striation formation are therefore conceptually and numerically compared in an attempt at arriving at a better understanding of this dynamic effect.

2. A MORE COMPLETE CHARACTERIZATION OF CUT QUALITY

Possibly the origins of many authors' work on laser modeling stemmed from early attempts by others to characterize the now well established fields of metal treatment, including welding, oxy-acetylene cutting, casting, flame-hardening and quenching. Although many years have passed since the fundamentals were first developed, the theory of moving point, line and plane sources of heat [10, 11] is one such famous area now receiving wide attention in general, and in the field of laser modeling. The Rosenthal solution for a moving line source [10] is given as

$$T - T_o = \frac{Q}{2\pi k d}\exp\left(+\frac{vx}{2a}\right) K_0\left[\frac{vR}{2a}\right]. \qquad (1)$$

Equation (1) assumes that the heat is absorbed uniformly along the plate thickness, and because the plate used in the experiments was relatively thin, this assumption has not been violated.

The shape of the melting isotherm can be obtained by the temperature distribution generated by the moving line source. Superposition of successive melting isotherms would lead to the generation of the cut edge profile if the frequency or spacing between each melting isotherm can be determined. A more complete characterization of the cut edge is therefore possible by a combination of frequency of striations or stria wavelength δ, depth of periodic structure formed between successive stria R_t, and kerf width of the cut b. Refer to Fig. 1.

The sideways burning theory suggests that at cutting speeds less than the speed of the reaction front, caused by oxidation, sideways burning occurs and results in the periodic forming of a stria. It has been shown previously that the reaction front for mild steel moves at a speed of about 2 m/min, independent of the laser power available [8]. This speed is limited due to the diffusion rate of oxygen into the melt. Because this is a necessary condition for sideways burning to occur, cutting speeds used in the experiments were kept below this value.

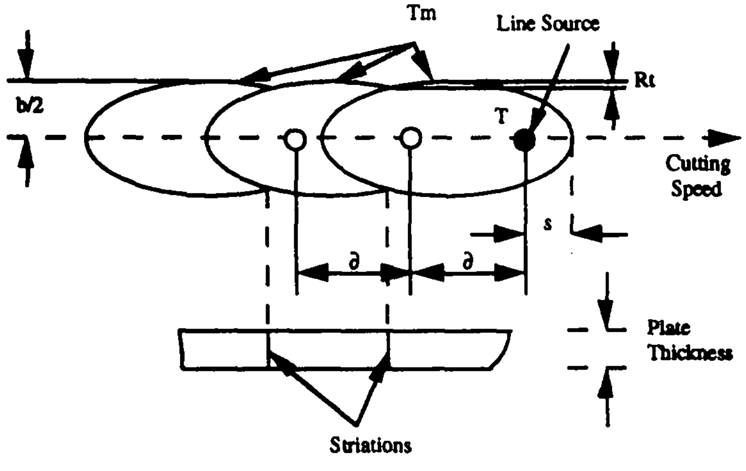

Fig. 1. Characterization of the cut edge.

3. EXPERIMENTAL SET-UP

The cutting experiments were carried out on a continuous wave "Laser Dynamics" slow flow CO_2 laser, capable of providing a maximum output of 450 W. A nozzle diameter of 0.5 mm was used and the focussed beam diameter was 0.25 mm.

The material used in all experiments was cold-rolled mild steel plate, with a nominal gauge thickness of 1.2 mm. The plate was guillotined into nine blanks of dimension 30 mm by 170 mm. A cut was produced along the length of each blank, 120 mm from one end. This allowed the kerf width and taper to be measured as well as allowing an investigation into possible topographical differences occurring on each corresponding cut edge. Each specimen was then sheared apart to allow profilometry and microscopic analysis.

Three levels of laser power and cutting speed were used whilst other parameters were fixed. A 3^2 full factorial experiment was designed. Table 1 shows the laser parameters selected for each cutting experiment. A constant oxygen supply pressure of 180 kPa was used for each specimen.

4. RESULTS AND ANALYSIS

The results show that "through cuts" were made on all specimens with the exception of specimen 9, where incomplete cutting was observed. A power reduction of 50 W and a cutting speed increase of 3 mm/sec over the conditions set for specimen 1 was sufficient enough to produce such poor quality cutting. This highlights the difficulty operators experience in "tuning" the laser parameters so as to achieve high quality cuts. It also highlights the need to maintain parameter drift to a minimum, especially over long operating periods and periods of un-manned operation.

A Nikon Shadowgraph machine was used to examine kerf widths and to measure heat affected zone extents. Heat affected zones were clearly indicated by observable crystal size and shape differences running along regular bands either side of the cut kerf. A Mitutoyo digital micrometer head facilitated accurate measurements.

A Talysurf 4 profilometer was used to examine cut edge attributes. The machine was capable of providing an arithmetical average (AA) surface roughness value denoted as R_a (cut-off length of 0.8 mm), a rectilinear profile of the surface traced by the stylus, and a peak height meter allowed maximum peak to valley (R_t) values also to be taken. All stylus traces were obtained along a parallel path a third of the way from the top face. A high resolution pick-up with a stylus tip width of less than 1.25 μm was used so that all significant features on the cut edge could be easily recorded. The stylus force was about 50 mg. In order to examine the cut edge topography, all profiles were digitized and recorded on a computer to facilitate the subsequent analysis. Figure 2 shows typical profile traces obtained from the cutting experiments.

The R_a values obtained showed that specimens 7 and 2 were the roughest surfaces traced, whilst specimens 4 and 8 had the smoothest edges. It was also observed that as the striation frequency increased, the surface roughness R_a decreased. This indicates that there is a strong relationship between striation frequency and cut quality. It is expected that if the frequency is increased indefinitely, then surface roughness should theoretically go to zero. It has been suggested that the number of striations per unit

Table 1. 3^2 factorial experiment

Laser Power (W)	Cutting Speed (mm/sec)		
	27	30	33
350	Specimen 4	Specimen 3	Specimen 9
400	Specimen 5	Specimen 1	Specimen 8
450	Specimen 6	Specimen 2	Specimen 7

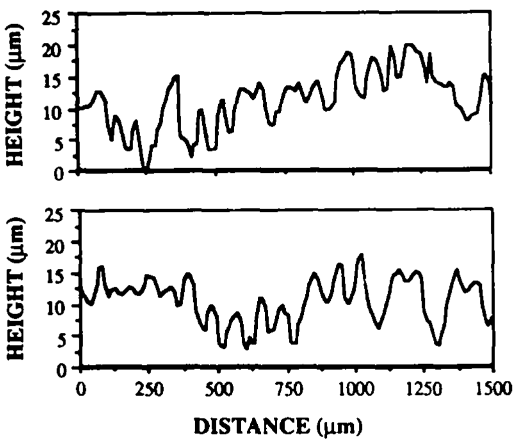

Fig. 2. Two typical profile traces produced.

length increases with speed increases up to the reaction front speed, but any speed increases over this do not result in further striation frequency increases [12].

4.1. *Determination of striation frequency*

For each specimen, the average wavelength of the periodic structure that appeared on the cut edges was experimentally determined. By knowing the processing speed at which the cuts were performed, the temporal frequency of each specimen was established. Figure 3 shows the periodic striation pattern observable in specimen 7.

4.1.1. *Striation frequency estimation by dispersion analysis based on ARMA models.* Time series techniques can be employed to analyze the dynamics found in the cut edge profile in a concise parametric way. Parametric modeling has its advantages in that it provides quantitative information about the system dynamics, and is not just qualitative. A discrete series of observations X_t, $t = 1, 2, 3, \ldots, N$, can be effectively

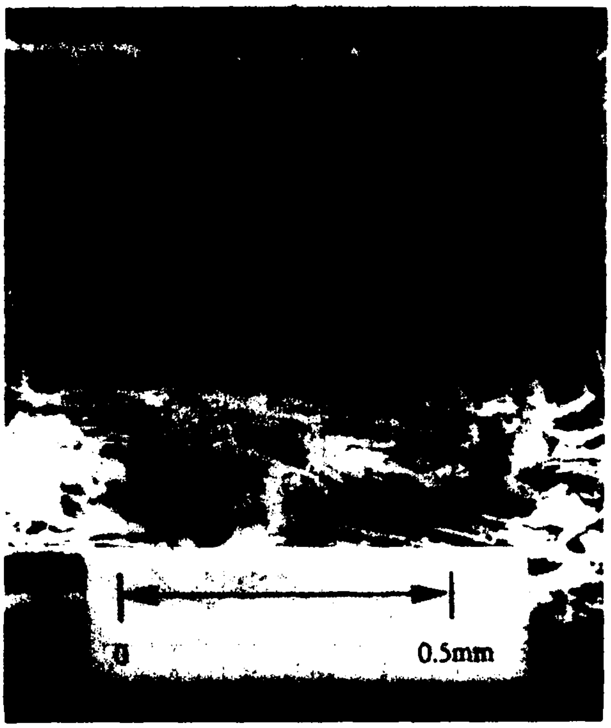

Fig. 3. The periodic striation pattern observed on specimen 7.

represented by the following equation, whereby both the dynamic and stochastic nature of laser cutting is incorporated.

$$X_t = \sum_{k=1}^{n} \phi_k X_{t-k} + a_t - \sum_{k=1}^{m} \theta_k a_{t-k}, \tag{2}$$

where a_t is white noise.

Equation (2) is known as an Autoregressive Moving Average model of autoregressive order n and moving average order m denoted by ARMA(n,m). The parameters ϕ and θ must be estimated, and the adequacy of the size of the model (determined by the orders of m and n) can be determined by the F-test [13].

Dispersion analysis can then be used to make discriminations amongst various modes of dynamic profile variations in a quantitative way. The dispersion percentage, D_i, describes the contribution of the roots or the frequencies in the series to the process variation. This is associated with eigenvalues (λ_i) occurring in complex conjugate pairs (λ_1 and λ_2). The frequency corresponding to these eigenvalues is given as

$$f_n\,(\mathrm{Hz}) = \frac{1}{2\pi\Delta}\sqrt{\left(\frac{[\ln(\lambda_1\lambda_2)]^2}{4} + \left[\cos^{-1}\left(\frac{\lambda_1+\lambda_2}{2\sqrt{(\lambda_1\lambda_2)}}\right)\right]^2\right)}, \tag{3}$$

where Δ is the sample interval in seconds.

Figure 4 shows the results obtained by the modeling procedure outlined above. It is evident that there is a close correlation with the actual striation frequency. This highlights the dominance of the striation frequency on the cut profile and consequently on the overall resulting quality achievable.

A linear regression analysis showed the existence of a strong correlation between the actual and modeled frequencies, however some deviation in the least squares approximation was observable. For a particular striation frequency, the modeled value always under-predicted it slightly. This can be attributed to several reasons, including the difficulty in accurately determining the number of striations per unit length per sample. If a different sample length or different location along the cut edge is chosen to determine these attributes, then discrepancies will arise because of the changing or unstable nature of a progressive cut. It could also be that such deviations occurred as a result of modeling a profile slightly different from the actual profile. No matter how much care is observed in obtaining profile traces, because a stylus tip always has a radius, some information loss is expected within the exploratory length. In addition, sampling of any analog or continuous output results in information loss.

4.1.2. *Comparison with theoretical studies.* It has been shown previously that oscillations of both the temperature and the thickness of the molten layer can occur with a time dependence or fluctuation of the laser power and the reactive energy gain. Fluctuations in the flow of the assist gas, material property variations and laser beam power fluctuations can bring about such oscillations and ultimately result in deviations

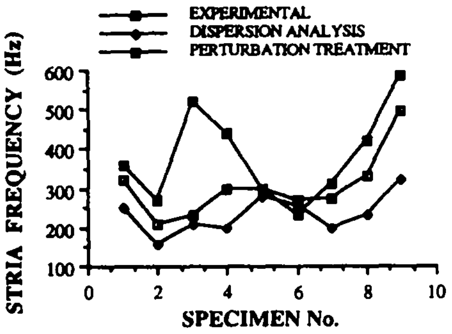

Fig. 4. Striation frequencies determined for each specimen.

in the quality of the cut edges. A dynamic energy and mass balance was derived as follows.

Energy balance:

$$aP_{\mathrm{L}}(t) + P_{\mathrm{R}}(t) - P_{\mathrm{loss}}(T,v) = c_{\mathrm{v}}dbs\frac{\mathrm{d}T}{\mathrm{d}t} + c_{\mathrm{v}}dbT\frac{\mathrm{d}s}{\mathrm{d}t}. \tag{4}$$

Mass balance:

$$m_{\mathrm{gain}}(v) - m_{\mathrm{loss}}(T,s) = Q_{\mathrm{m}}db\frac{\mathrm{d}s}{\mathrm{d}t}. \tag{5}$$

$P_{\mathrm{loss}}(T,v)$ is made up of losses such as conduction, evaporation, convection, melting and heating whilst $m_{\mathrm{loss}}(T,s)$ is made up of mass losses such as evaporation and friction between the melt and the reactive gas flow. The above energy and mass balance were linearized using a small perturbation treatment with success.

$$s_1'' + \beta s_1' + w_0^2 s_1 = [aP_{\mathrm{L1}}(t) + P_{\mathrm{R1}}(t)]\left(\frac{\delta m_{\mathrm{loss}}}{\delta T}\right)_0 \frac{1}{C_{\mathrm{v}}dbs_0\,Q_{\mathrm{m}}db}, \tag{6}$$

where

$$w_0^2 = \left(\frac{\delta P_{\mathrm{loss}}}{\delta T}\right)_0 \left(\frac{\delta m_{\mathrm{loss}}}{\delta s}\right)_0 \frac{1}{C_{\mathrm{v}}dbs_0\,Q_{\mathrm{m}}db}. \tag{7}$$

In [14] it was shown that the liquid layer thickness can be given by the shortest distance from the line source to the melting isotherm. Refer to Fig. 1. The values b and s used here were the values already calculated from the isothermal description. The results for the striation frequencies calculated are given in Fig. 4. They too show close correlation both with the actual values obtained and with those estimated by the dispersion analysis.

4.2. *Determination of depth of periodic structure*

4.2.1. *Determination of depth of periodic structure based on dispersion analysis and solution of the moving line source.* It follows that once the melting isotherm and wavelength of the striations are known, then by superposition of successive isotherms, the surface roughness index, R_{t}, the maximum roughness height, can be evaluated. Figure 5 shows the cut edge profile observable in specimen 9.

For each specimen, the maximum roughness height, R_{t}, was calculated, the results of which are shown in Fig. 6. These correlated well with the experimentally obtained results. Again slight under-prediction is observable. It is expected that the same reasons hold true as for the discrepancy in determining the frequencies.

4.2.2. *Comparison with theoretical studies.* It has been shown previously that if the term $aP_{\mathrm{L1}}(t) + P_{\mathrm{R1}}(t)$ in equation (6) is lumped together so that it will oscillate as a whole, i.e. $aP_{\mathrm{L1}} + P_{\mathrm{R1}} = \mathrm{Re}\,\{\Delta p \cdot e^{jwt}\}$, then the solution of equation (6) can be used to determine the depth of the striation pattern. Results have shown that only reasonable order of magnitude values are obtainable. This is due to several reasons, including the reliance on accurately predicting the size and frequency of the lumped absorbed laser power and reaction energy, if indeed, such lumping is realistic. It is argued that the absorbed power would exhibit a range of dominant frequencies far different from that of the reactive gas flow. The results also assume that a kerf width fluctuation is a direct result of the same size fluctuation in the molten layer thickness. This would clearly not be the case. This is expressed in the following form.

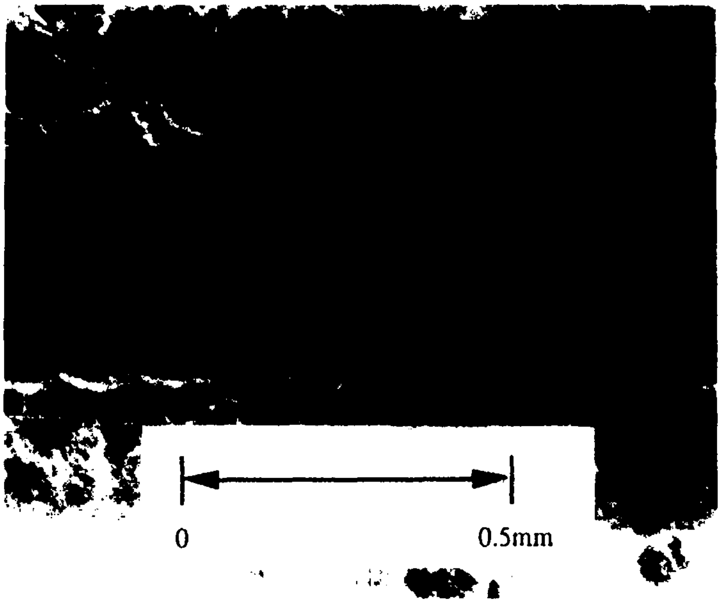

Fig. 5. The edge profile observed in specimen 9.

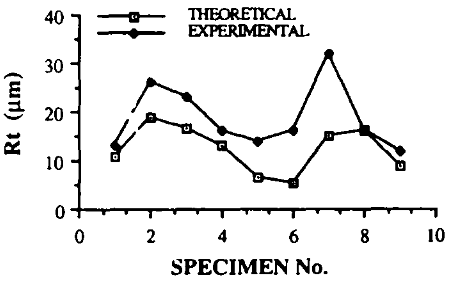

Fig. 6. R_t values for each specimen.

$$b_{l\max}/b = s_{l\max}/s_0\,, \tag{8}$$

where $b_{l\max}$ and $s_{l\max}$ are the maximum values of the oscillating width and molten layer thickness, respectively.

5. DISCUSSION

The results have shown that the new technique developed is capable of characterizing the resulting profile generated by laser cutting. The two quality indices estimated, namely the periodic frequency and depth, were in good correlation with the actual profiles obtained. This paper strongly supports the sideways burning theory for the mechanism governing stria formation.

It was also shown that there was good agreement with theoretical investigations undertaken previously, although these models assumed a different mechanism for the forming of striations. It is possible that more than one mechanism for this periodic structure could occur in tandem.

The liquid layer oscillation theory can reliably predict an oscillation on the steady state molten layer thickness, although the results for the depth of the periodic structure show only approximate order of magnitude. This mechanism for striation formation is likely, and processing speeds are not limited to below the reaction front speed as is the sideways burning theory.

It is possible to argue that the molten layer oscillations may occur simultaneously with the dominant sideways burning mechanism at speeds less than the reaction front speed. At higher speeds, though, the molten layer oscillations become dominant and sideways burning ceases to occur. Having two mechanisms for striation formation also accounts for the fact that striations occur in inert gas jet cutting, where sideways burning cannot exist, indicating that more than one mechanism for striation formation must be possible. The following reasons are given.

As the speed increases, the inclined cutting front angle increases and therefore a larger pressure gradient will result within the cutting zone. This would generate a transition from laminar gas flow to turbulent gas flow and thus melt removal instabilities and reaction energy instabilities would result, if indeed laminar flow is genuinely possible at all in gas assisted laser cutting.

With cutting speed increases, the molten layer thickness increases because more molten metal exists in the kerf per unit time [15]. Therefore this will result in a more pronounced spatial distortion on the cut edges, induced by the molten layer oscillations.

As speeds increase, melt flows move from one-dimensional to two-dimensional melt flows, as shown by spark shower experiments [16]. The mechanism governing the liquid layer oscillation theory suggests that horizontal pulsations occur prior to melt ejection, indicating two dimensionality. This is suggestive that as speeds increase, the mechanism governing striation formation moves from the sideways burning theory to the liquid layer oscillation theory.

6. SUMMARY

In an attempt at improving laser cutting quality, the present authors have characterized the resulting topography through two quality indices under different cutting conditions. A new technique for obtaining the striation frequency led to the first real attempt at characterizing the striation depth. Auxiliary information such as kerf width can also be ascertained using this methodology. It was shown that dispersion analysis provided a sensitive means of capturing the dynamics present in the cutting process in order to obtain the underlying frequency, and that by the superposition of successive isotherms, the laser cut profile can be successfully generated.

It is argued that neither the sideways burning theory not the liquid layer oscillation theory can be dispelled, although the latter cannot reliably predict the depth of the striation pattern as did the conceptual model developed, essential for addressing the whole issue of cut quality. At speeds less than the reaction front, both mechanisms occur simultaneously with sideways burning being predominant, whilst at higher speeds above the reaction front speed, sideways burning ceases and liquid layer oscillations increase, due mainly to the increase in turbulence and the thickness of the molten layer associated with such cutting speed increases.

In conjunction with theoretical models undertaken previously, this technique also allows for the prediction of expected cut quality prior to machine operations. Currently, the feasibility of obtaining the striation frequency on-line is being assessed through different sensing techniques. It is expected that this will allow real-time monitoring and prediction of cut quality through an extension of the work presented in this paper. Results are to be published shortly.

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