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V.C. VENKATESH

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IZMAN SUDIN
ZAINAL ABIDIN AHMAD
SAFIAN SHARIF

Department of Production and Industrial Engineering
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
Johor, Malaysia

Effects of Workpiece Boundary and Motion on Laser Cutting Front Phenomena

P. Di Pietro[a] and Y.L. Yao[b*]

[a]School of Mechanical and Manufacturing Engineering, The University of New South Wales, P.O. Box 1, Kensington, NSW 2033, Australia

[b]Department of Mechanical Engineering, Columbia University, 220 S.W. Mudd Building, New York, NY 10027, USA

ABSTRACT

A transient two-dimensional model is developed and numerically solved to specifically investigate the effects of CNC motion and workpiece boundary on cutting front mobility and temperature in reactive-gas assisted CO_2 laser cutting. Co-ordinated motion systems must ramp up and down to their desired speeds, and therefore the initial actuator acceleration is considered for its effect on the cutting front phenomena. Boundary encroachment and bulk heating effects due to the workpiece boundary are also studied for their effect on the phenomena. Final actuator deceleration to workpiece edges reduces the amount of beam coupling arriving to the material and thus reduces such bulk heating effects. The results show that appropriate part programming of the laser system can help minimise the effect of boundary and motion on quality degradation. A more realistic temperature distribution of the workpiece was also obtained from the model by explicitly considering the presence of the kerf and making nodal points within it part of the convective environment. Results on front mobility and temperature show similar trends as experimental results elsewhere whilst their direct verification is currently under investigation.

NOMENCLATURE

a_c	acceleration value	P_{exo}	exothermic power
amu	atomic mass units	P_{inc}	incident beam power
b	kerf width	P_{melt}	melting power
c_v	heat capacity	ρ	density
D	workpiece thickness	$\dot{q}$	heat generation
h_c	convective heat transfer coefficient	S	molten layer thickness
h_r	radiative heat transfer coefficient	S_b	distance beam has moved from its previous location
ΔH	exothermic energy release for iron	S_f	distance front has moved from its previous location
k	thermal conductivity	T	temperature
L	workpiece length	t	time
L_f	latent heat of fusion	V_b	velocity of laser beam
$\dot{m}$	melt removal rate	V_f	velocity of cutting front
P_b	beam power	W	workpiece width

* Author to whom correspondence should be directed.

1. INTRODUCTION

Most laser cutting applications today are of the two-dimensional contour type. Efforts in laser cutting research have so far concentrated almost exclusively on the simple case of linear constant velocity cutting. Admittedly, this is an appropriate area to investigate initially, but greater efforts are now needed to investigate more complex areas of concern. As we move from the realm of one-dimensional processing to two or more dimensional processing, we need to consider non-linear effects such as the dynamics of the handling system. With quality and productivity being of the utmost importance in today's economic climate, laser cutting cannot be perceived as simply a laser source, but needs to be considered as an overall system. CNC systems therefore need to be specifically tailored to the laser cutting industry. A greater understanding of the effects of such controllers on the cutting process is therefore necessary. In reality, co-ordinated motion systems must ramp up and down to desired target speeds in order to perform the part-programme generated. In cases where applied heat fluxes are strong enough to melt the material though, the problem becomes complex due to the moving solid-liquid interface. Associated with this effect is the issue of non-linear beam coupling to the workpiece. Such accelerations will cause the cutting front to move at different rates to that of the beam. Even in the simple case of constant velocity cutting, the solid-liquid interface can move considerably when approaching the workpiece boundary.

The most common assumption made in previous attempts at characterizing the process is that of infinite workpiece length [1]. Too often boundary conditions are trivialized by prescribing fixed boundary temperatures. Boundaries can be present in laser cutting in the form of workpiece edges or pre-cut sections, and are especially significant in laser cutting of intricate parts. It is obvious that as the amount of heat accumulation to an area changes as in the case with a boundary encroachment, the cutting front can move significantly. Ideally for high quality cutting, the heat flux per unit time at the cutting front should always remain a constant. Any changes in this will be clearly observable by either increased dross attachment, roughness of cut or kerf widening. Geometrical effects in a part to be laser cut therefore cannot be neglected, and how they are negotiated often determine if a cut is deemed successful or not. Other geometrical effects include entry holes and sharp corners. Appropriate part-programming of the laser system can help to minimise their effect on quality degradation.

Because of the analytical difficulty in addressing such problems, not a great deal of work has been previously undertaken. Investigations into the cutting front mobility have been carried out [2]. High speed photography of the cutting front showed it to be dynamic in nature The formation of striations on the kerf edges are explained well by the relative motion of the front past the laser beam due to the exothermic reaction. The front then subsequently extinguishes, whereby re-initiation of the reaction occurs as the beam overtakes the front, and so the oscillation continues. It has been argued that power fluctuations can induce both temperature and molten layer thickness oscillations, thus causing striations to occur [3]. Such oscillations are indicative of the dynamic nature of the cutting front. A mono-dimensional finite difference model also clearly demonstrated that the front could possess mobility when cutting at constant processing speeds [4].

In this paper, a numerical model is developed in order to investigate the effect of various velocity profiles on the cutting front temperature. The model is solved by using the finite difference method. Inherent problems associated with a moving cutting front are resolved. These issues require a numerical approach, which would otherwise be impossible to address analytically.

2. THEORETICAL BACKGROUND

The starting point for any transient heat transfer analysis is the general heat conduction equation for an isotropic solid continuum. This suggests that for any such element, the net heat conducted in plus the heat generated within equals the elemental energy increase. If we assume constant thermo-physical properties and that the temperature distribution is homogeneous along the depth of the workpiece i.e. $\partial T/\partial z=0$ as is the case with thin plate laser cutting, then this reduces to the simpler two-dimensional transient heat conduction equation of the form:

$$\frac{k}{\rho c_v}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{\dot{q}}{\rho c_v}=\frac{\partial T}{\partial t} \tag{1}$$

It is assumed that the initial temperature distribution at time $t=t_o$ is given as $T(x,y,t_o) = T_\infty(x,y)$, where T_∞ is ambient room temperature. Naturally boundary conditions must be specified at every boundary point. Often prescribed temperatures are given, but in practice this is clearly inappropriate as discussed previously. A much more acceptable boundary condition allows convection and radiation to occur to the surroundings with constant conditions h_c and h_r:

$$-k_b\frac{\partial T}{\partial n}\Big|_b=(h_c+h_r)(T_b-T_\infty) \tag{2}$$

where n denotes the outward-normal co-ordinate from the boundary and subscript b denotes a boundary point. In this situation, the boundary temperatures are not known until after the solution is determined. The radiative heat transfer coefficient must be determined prior to the use of Eqn. (2) as

$$h_r=\varepsilon\sigma_b(T_b+T_\infty)(T_b^2+T_\infty^2) \tag{3}$$

where ε is emissivity and σ_b is the Stefan-Boltzman Constant. Because of its fourth-power relationship with temperature, radiation becomes dominant at high temperatures, as in the case of laser cutting. Although the workpiece temperature falls dramatically with increasing radial distance from the cutting zone, this heat transfer mechanism is included everywhere for the sake of completeness.

At all points other than where the oxygen gas jet impinges, it is assumed that there is no farfield streaming and thus natural or free convection occurs. However underneath the cutting nozzle, forced convection is apparent and thus the resultant heat flux will generally be far greater than in the free convection case. Fully developed turbulent flow in a smooth tube is assumed for the forced convection. Although the free convection contribution is relatively small, it is too included for the sake of completeness.

The energy produced by the exothermic reaction cannot be neglected as its contribution is generally of the same order of magnitude as the absorbed laser beam power. It has been shown previously through an ejected particle analysis that approximately 50% of the melt ejected from the kerf is Fe and the remainder is almost completely FeO [5]. Assuming a pure oxygen supply for the assist gas, the following reaction occurs within the cutting kerf: $Fe + 0.5\ O_2 = FeO$ and ΔH = -257.58 kJ/mol, where ΔH is the energy released during the reaction and the ignition point is 1473.15K [6].

If the mass removal rate of the melt out of the kerf is known or can be calculated, then the following relationship can be used to determine the energy obtained by reaction.

$$P_{exo}=\frac{\dot{m}\Delta H}{2amu} \tag{4}$$

where amu = 1 mole FeO = 71.847 g/mol

Because the material within the kerf is melted and then expelled out, it is necessary to consider latent heat effects. In laser welding this is often neglected because the latent heat of fusion is compensated by the latent heat of solidification. In cutting though, the material is removed and as such, only a very small liquid layer along the walls of the kerf can contribute to this heat of solidification.

$$P_{melt} = \dot{m}L_f \tag{5}$$

where $L_f = 275$ kJ/kg

It has been assumed previously that the material removal rate can be given approximately by the following equation [7]:

$$\dot{m} = \rho\, b\, D\, V_b \tag{6}$$

This is only true though when it is assumed that the processing speed equals the front speed as in steady state cutting. In reality though, the front speed is the factor affecting the mass removal rate and not the cutting speed. The mass removal rate is therefore given as:

$$\dot{m} = \rho\, b\, D\, V_f \tag{7}$$

Because kerf width fluctuations are generally small for high quality cutting, it is assumed that they are negligible and that the width is approximately of the same extent as that of the laser spot diameter. Such fluctuations have been considered elsewhere [8].

3. NUMERICAL MODELING

The determination of the mass removal rate is dependent upon firstly evaluating the cutting front speed. From Fig. 1, it can be shown that:

$$\Delta S_f = \Delta S_b - S + (S + \Delta S) = \Delta S_b + \Delta S \tag{8}$$

In the time interval Δt, an expression for the front velocity can be ascertained:

$$\frac{\Delta S_f}{\Delta t} = \frac{\Delta S_b}{\Delta t} + \frac{\Delta S}{\Delta t} \tag{9}$$

The limit as $\Delta t \to 0$, yields the following instantaneous rates of change:

$$\frac{\partial S_f}{\partial t} = \frac{\partial S_b}{\partial t} + \frac{\partial S}{\partial t} \tag{10}$$

From which Eqn. (9) can be expressed in the general form:

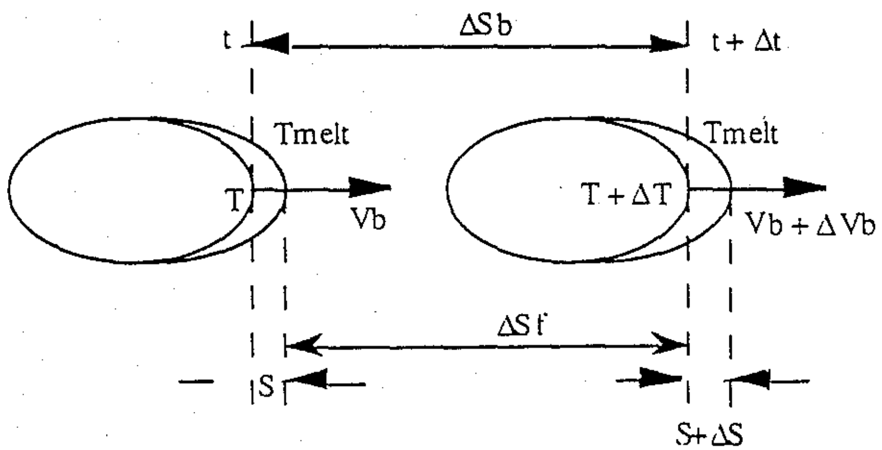

Figure 1. Generation of Cutting Front Mobility

$$V_f = V_b + \frac{\partial S}{\partial t} \tag{11}$$

where $\frac{\partial S}{\partial t}$ is the time rate of change of the molten layer thickness.

The velocity of the cutting front can be used to solve complex issues involved in acceleration and deceleration routines. When a laser beam accelerates , the beam tends to ride ahead of the cutting front and thus efficient laser coupling is obtained as all the beam power arrives on the un-molten workpiece. But when the laser beam decelerates as is often the case in approaching a corner or negotiating a complex contour, the beam tends to lag behind the front and thus some portion of beam power will pass straight through the kerf providing little or no contribution to heating and melting the workpiece. This inefficiency of the process caused by the dynamics of the motion system and cutting front needs to be accounted for when CNC contour control is used in laser processing.

Prior to a decelerating profile, all the beam power is assumed to fall upon the un-molten work material as in the case in constant velocity or accelerating cutting conditions. This is typical in high quality industrial laser cutting. In a time period Δt, the distance moved by the laser beam under a constant deceleration is given by:

$$S_b = V_b \Delta t + 0.5 a_c \Delta t^2 \tag{12}$$

In the same time period, the distance the front moves is greater, because there is no deceleration in the first instance of the beam retardation.

$$S_f = V_f \Delta t \tag{13}$$

The percentage of power lost is then given by the proportion the front is ahead of the trailing edge of the laser beam. It cannot be simply assumed that the front will continue indefinitely at this speed. In fact, the front speed will decrease because the power input to the cutting zone has been reduced significantly due to the deceleration. This means that the dynamics of the front inhibits the proportion of energy lost through the kerf because the front quickly responds to the power loss and quickly decelerates as well.

4. SOLUTION APPROACH

Thin plate laser cutting reduces to the case where the temperature distribution is homogeneous along the depth of the workpiece. Only half of the workpiece width is considered as the temperature distribution is symmetrical about the OY axis. This eases computational effort and reduces the time requirement for solution. In doing so, the OY axis boundary in effect becomes an insulating surface, as no heat flux crosses it. After material is expelled from the kerf, conduction cannot occur across this region as these points are now part of the free convective environment. The model accounts for this by checking all nodes above melting temperature which have been previously processed by the laser beam and fall within the extent of the gas stream, which forces the melt out of the kerf. This free convection effectively cools the cut face and the heat flux tends to move in a normal direction to this edge.

Heat diffusion equations are determined for all nodal points, both within the control volume and at boundaries. These balance equations can be solved in a number of ways. The explicit form is most appropriate for computer use and extremely fast, and was originally used. A numerical stability condition limits the time step Δt, so that divergent oscillations of the calculated temperatures are avoided. This condition made it impossible to study various CNC acceleration and deceleration curves and thus the implicit method was reverted to. The implicit method has unlimited numerical stability but is more difficult to solve as a set of simultaneous equations ensues. The Gauss-Seidel iteration method was used to solve these equations. All nodes were swept by their appropriate equations until the temperatures converged to some previously set limit.

5. DISCUSSION OF RESULTS

Results are presented in the order of how a cut would normally be performed in practice. This sequence starts with cut initiation issues and ends with either cut termination to a boundary edge or deceleration to a specific point within the workpiece.

5.1. Actuator Acceleration

The next stage in the cutting sequence involves command generation which will allow the cutting action to commence. The generation of such commands is extremely important and determines the success of the overall 'laser system', which includes not only the laser source but also the machine or CNC control system. Large axis inertias and actuator torque limitations must be investigated, and precise control of axis acceleration, velocity and position are essential for successful implementation. Only constant-acceleration profiles were investigated. The model was run under this condition to obtain cutting front temperature and cutting front velocity. Fig. 2(a) shows the cutting front temperature obtained as a function of processing time after initially drilling the blast hole.

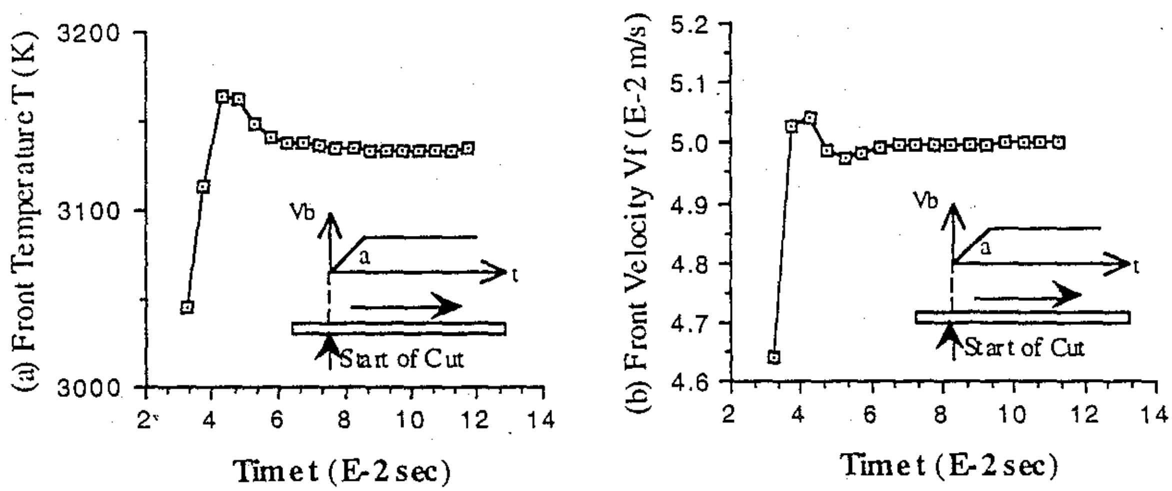

Figure 2. Effect of Acceleration on (a) the Cutting Front Temperature and (b) the Cutting Front Velocity. P=810W, D=1.2mm, Acceleration = 1.667m/s^2, V_b = 50mm/sec

It can be seen that the temperature reaches a maximum at 42.5 msec and then gradually decays until a steady state temperature is reached at 0.1075 sec. This translates into a distance of 4.75 mm after the blast hole where transience is still present. This unstable zone will be accommodated generally with material overheating and uncontrollable burning, kerf widening and excessive surface roughness.

Fig. 2(b) shows the cutting front velocity determined during the cut. It can be seen that it exhibits oscillatory decay as opposed to the steady decay of the front temperature. The front velocity increases quickly, overshoots the desired processing speed of 50 mm/sec and then oscillates until it stabilises to the processing velocity, in similar fashion to the response of an under-damped second order system.

5.2. Constant Velocity Cutting

Once steady state has been reached, the temperature will be maintained until a boundary is encroached upon. Rust, scale and material imperfections may cause some imbalance. Fig. 3 shows the resulting isothermal description of the cutting process at a particular instant in time. The isotherms will change both in shape and size as time progresses because the model considers multidimensional unsteady heat conduction. Note the presence of the kerf along the centre of the workpiece makes the isotherms above deviate from the classical 'egg' shaped isotherms that are well known for moving sources of heat.

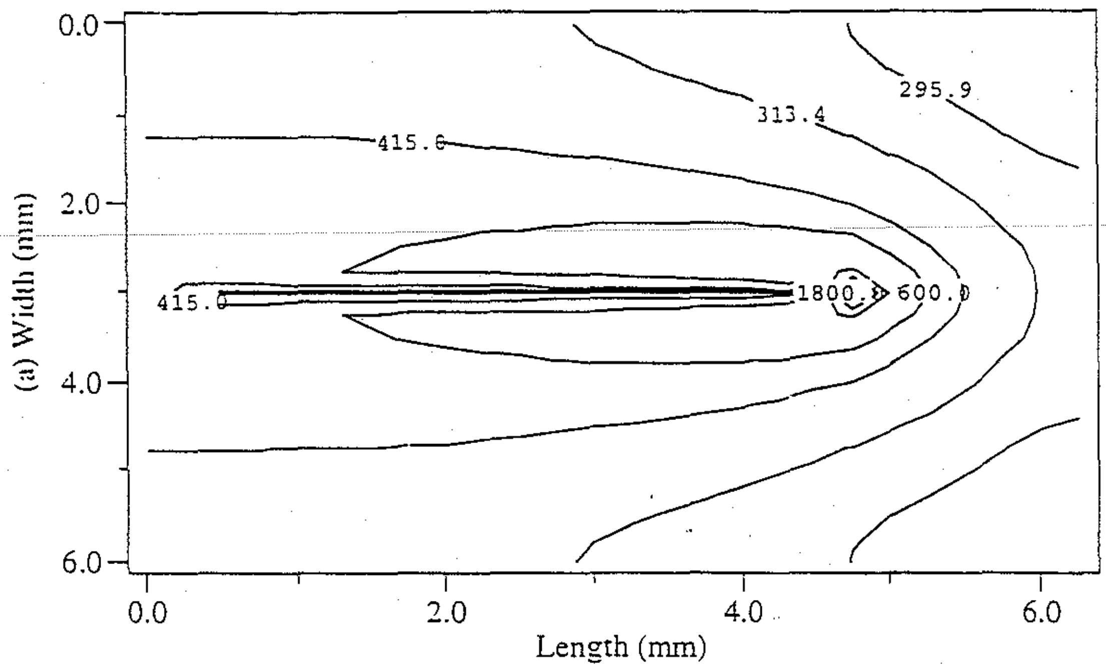

Figure 3. Contour Plot of the Workpiece Temperature Distribution at time t=0.1075sec. P=810W, D=1.2mm, Acceleration = 1.667m/s^2, V_b = 50mm/sec

5.3. Boundary Encroachment

Fig. 4(a) shows that the cutting front temperature increases quite dramatically as a boundary is approached. This represents an increase of 11.9% over the steady state temperature. Such increases are typical in practice. As the beam approaches the boundary, it can be seen from Fig. 4(b) that the velocity of the front increases dramatically from the constant beam velocity V_b = 50 mm/sec. Again because of the bulk heating effects apparent in this region, heat diffusion is more difficult and thus the front begins to increase in speed as the material begins to heat up at a quicker rate than previously.

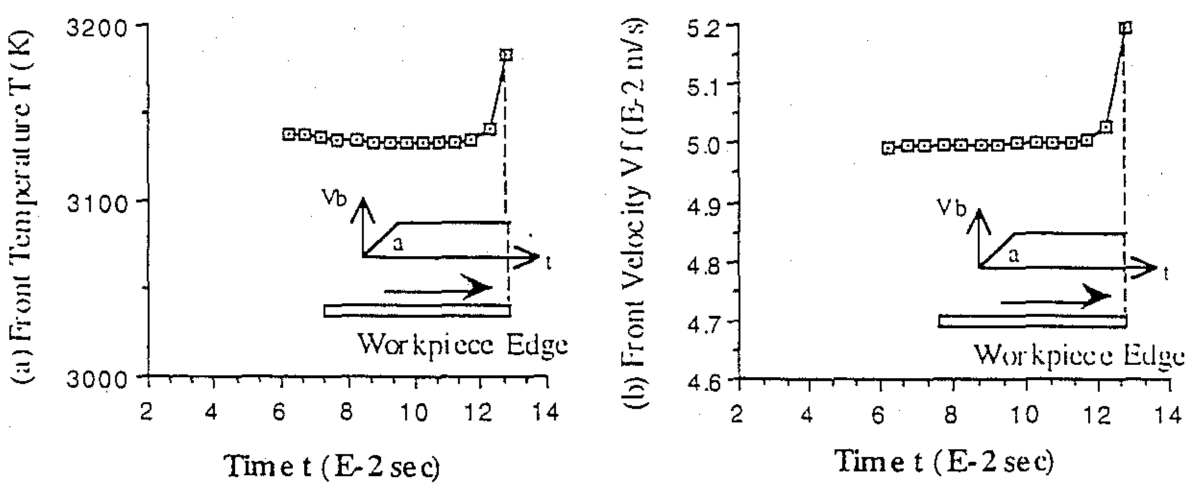

Figure 4. Effect of Boundary Encroachment on (a) the Cutting Front Temperature and (b)the Cutting Front Velocity. P=810W, D=1.2mm, Acceleration = 1.667m/s^2, V_b = 50mm/sec

5.4. Implication of Actuator Deceleration

In many situations in computer controlled systems, axes must decelerate to negotiate corners or to follow a prescribed complex path such as in bi-axis co-ordinated circular motion profiling. As mentioned previously, when we accelerate or cut at a constant velocity, the beam tends to couple efficiently with the work material and can be assumed so in most practical situations. When the laser beam decelerates quickly, the dynamics of the front cannot be neglected and it cannot be assumed that the front responds immediately to the velocity profile change. In reality, in the first instance, the front will continue at its current speed and thus the beam power falling upon the unmolten material is reduced by some percentage. In the next time interval, the front velocity will reduce because of the lower amount of energy input to the front. This will result in greater beam coupling if it decelerates at a quicker rate than the beam is decelerating, or otherwise, the beam coupling will reduce once again.

Refer to Fig. 7(a). It can be seen that the cutting front temperature is dramatically reduced as a result of the deceleration. This decrease can be explained if we consider what percentage of beam power falls onto unmolten material. Fig. 7(b) shows that as we decelerate, the power steadily falls off, providing less heat flux at the front and hence the lower temperatures experienced here. Refer to Fig. 7(c). When we decelerate it is evident that the front speed overtakes the cutting speed quite considerably and thus power is lost through the kerf. It then slowly approaches the cutting speed once more.

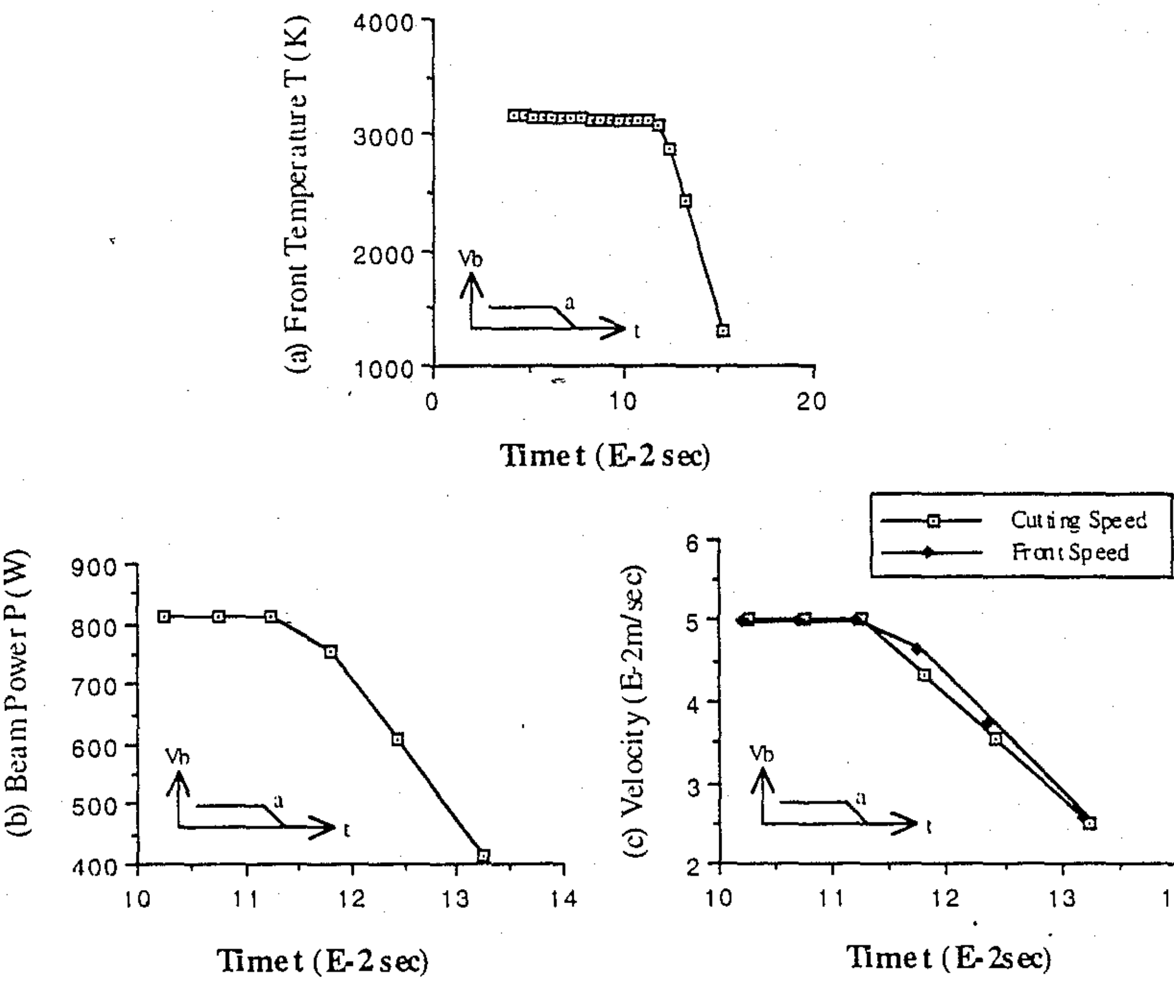

Figure 7. Effect of Deceleration on (a) the Cutting Front Temperature, (b) the Beam Power Falling on the Front, (c) the Cutting Front Speed.

P=810W, D=1.2mm, V_b=50mm/sec, Deceleration=-1.25m/s^2

6. CONCLUDING REMARKS

The numerical model developed examined various CNC velocity profiles for their effect on the resulting cutting front temperature. As such, issues such as cutting front mobility and temporal beam coupling effects are resolved. The presence of the kerf was considered and became part of the convective environment. This made diffusion more difficult and forced the front temperature higher than would be expected from well behaved analytical models (which simplistically allow conduction to occur across such boundaries).

Typical initial actuator accelerations were considered for their effect on both the resulting cutting front temperature and front velocity response. The implication of actuator retardation was shown to result in a reduction in the amount of beam coupling and hence an associated temperature drop was evident. Boundary encroachment and bulk heating effects (due to workpiece geometry) caused the front velocity to increase dramatically on approach to a workpiece edge.

The results from the numerical investigation above indicate that appropriate part programming can help minimise these effects on quality degradation. The initial acceleration should be properly selected to minimize its influence on cutting front mobility and temperature. Appropriate deceleration profiles should be determined as the beam approaches the workpiece boundary. Because of the bulk heating in this region, heat diffusion is more difficult. Appropriate decelerations would result in larger portions of beam power falling through the kerf and as such, the heat flux per unit time at the cutting front could remain more uniform. Use of various non-linear cutting speed profiles are currently under investigation. The front temperature obtained reasonably agrees with that found experimentally [2] and cutting front mobility results exhibit similar trends to those found in [4]. The effectiveness of existing experimental methods and alternatives for model verification are under investigation.

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