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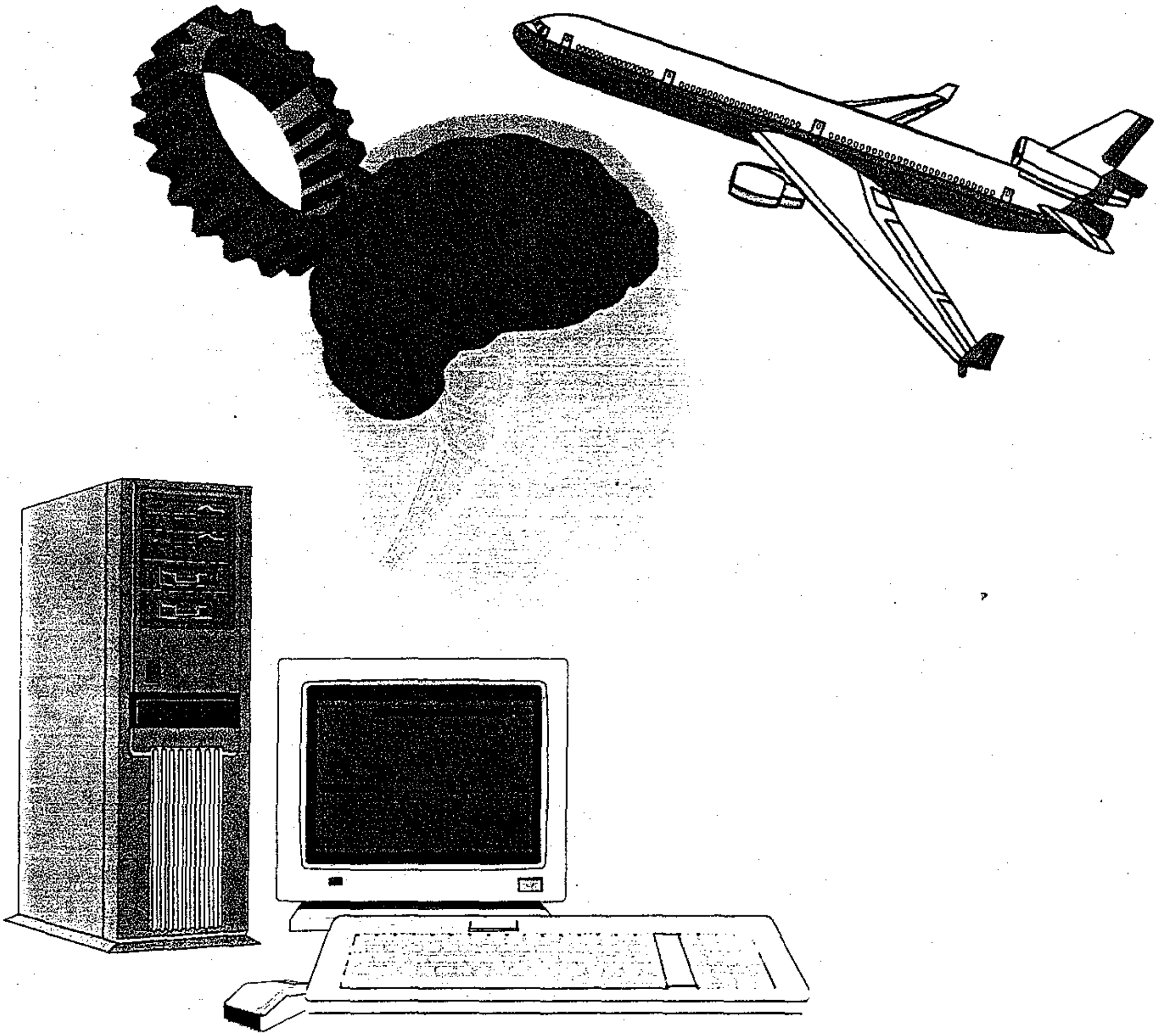

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IMPROVING LASER CUTTING QUALITY FOR TWO-DIMENSIONAL CONTOURED PATHS VIA MODEL-BASED OPTIMISATION

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ABSTRACT

Quality improvements in laser cutting of mild steel have been achieved by a newly developed model-based optimisation strategy. The specific aims of such efforts are to assure quality of cut when cornering. Such routines encompass a large proportion of all features processed on laser cutting systems, and therefore their successful production is paramount. Associated with cornering is the elevation of workpiece temperature in the vicinity of the cut. This is because of the increased beam exposure time due to reduced cutting speeds associated there. Corner melt-off is therefore common.

In order to focus on the development of such optimisation, constant thermo-physical properties and two-dimensional transient heat conduction are simply assumed. The model is therefore valid for the thin plate laser cutting case, where temperatures are approximately homogeneous with workpiece depth. Non-linear power adaption profiles are generated via the optimisation strategy in order to stabilise cutting front temperatures. Uniform temperatures produce better quality by reducing i) kerf widening effects, ii) heat-affected zone extents, and iii) workpiece self-burning effects. At the very least, uniform cutting front temperatures reduce the variability in cut quality which increases the odds that the final workpiece will reach acceptability standards. Currently, extensive trial-and-error based experimentation is needed in order to improve quality for these routines. Thus model-based optimisation has the added benefit of reducing this time-exhaustive step whilst leading to an optimal solution. Experimental results are presented, and it is demonstrated that such process manipulation can produce significant quality improvements.

INTRODUCTION

Today, laser cutting of highly complex and intricate workpieces is a reality. Of concern though, is the effect of part geometry on the quality achievable. Such part programs typically contain many pre-cut sections and boundaries, and because of the obvious size of such workpieces, heat accumulation is often severe. This can result in poor cutting quality in the form of widespread burning, increased dross, increased surface roughness, increased heat-affected zone, and kerf widening being common amongst other problems. The appearance of even one of these anomalities can render the complete job useless.

In cases where heat fluxes are strong enough to melt the material as in laser cutting, the problem becomes complex due to the moving solid-liquid interface. Efficient cutting occurs when the beam rides ahead on the unmolten material and therefore little energy falls through the generated cut. When the cutting front speed increases due to heat accumulation, or when cutting at slow processing speeds, the beam tends to lag behind the front. As a result, much more laser beam energy passes through the cut with little or no heating effect. Such characteristics of the process alter the amount of energy input into the interaction zone, and therefore cutting front temperatures are expected to change.

Consequently, such temperature deviations are attributable to the generation of inconsistent cut quality.

There have been many models developed over the years to describe the laser cutting process. A comprehensive review of these is given elsewhere by the authors Di Pietro and Yao (1994). In particular, Gonsalves and Duley (1972) first accounted for the fact that only part of the incident beam power is available for laser cutting sheet metals. This fraction was determined using a moving point source model. The model was used to determine the interrelationship between cutting speed, cut width and power required for efficient laser cutting. Powell (1993) devised cutting experiments to investigate the transmission and reflection losses occurring in the cutting process based on previous work done by Miyamoto et al. (1984, 1986). It was shown that the amount of reflected/transmitted light reduced as sample thickness was increased. Schreiner-Mohr et al. (1991) also conducted experimental work which showed that at maximum cutting speeds, the beam centre can precede the front location. At slow cutting speeds the beam centre was shown to lag behind the cutting front. A finite difference model for laser cutting thin metallic glasses was also conducted (Glass et al., 1989). It accounted for proper material removal by including the energy lost through the kerf by removing those nodes above the melting temperature. A mono-dimensional finite difference model was proposed by Yuan et al. (1988) which suggested that the cutting front could possess mobility when cutting at constant processing speeds. Arata et al. (1979) showed through high speed photography that the cutting front was indeed dynamic in nature, and the formation of striations on the kerf walls could be explained well by the relative movement between the front and the laser beam.

Previous attempts at characterising the process have often assumed infinite workpiece length or they have prescribed fixed boundary temperatures. But in laser cutting of intricate parts, this assumption leads to low heat accumulation estimates. Such simplifications allow the general heat conduction equation to revert to the case of steady multi-dimensional conduction. A transient model was therefore developed to account for workpiece geometry and the presence of a kerf is considered, with nodal points within it becoming part of the convective environment. Thin plate laser cutting is considered, so that the model can assume the two-dimensional heat conduction form in order to reduce the complexity of the optimisation tasks. Inherent problems associated with a moving cutting front and temporal variations of the energy input per unit time are resolved. These issues require a numerical approach, which would otherwise be impossible to address analytically.

BACKGROUND

Simple observation of laser-cut corners show that in most cases, corner tip melt-off is common. This is due to the increased time the laser beam is in this area due to the deceleration of one axis, and then acceleration of the other to perform the desired task with adequate positional control. Many systems now allow the adaption of laser power when cornering to compensate for the reduced cutting speeds associated there (Leece, 1984, Delle Piane, 1985, VanderWert, 1985, Steen and Li, 1988, and Powell, 1993). This was possible through advances made in controller design. Such adaption ensures that the rate of energy input into the interaction zone and the rate of melt ejection from the kerf is kept somewhat balanced. This technique can be used either under continuous wave (CW) or pulsed mode operation.

The determination of this power-feed ratio currently relies on extensive experimentation. One method of achieving this control feature is by varying the pulse frequency and/or pulse length proportionally to the feedrate (Moriyasu et al., 1986, Schuocker and Steen, 1986, Borgstrom, 1988, and Schwarzenbach and Hunziker, 1988). Such duty cycle modulation produces very accurate control of the laser output by altering the precentage of beam 'on-time' to suit the feedrate.

If the system can respond quickly to power commands from the controller, then the input current to the laser can be manipulated for an effective power-feed strategy. Another approach is termed channel switching (Hertzel, 1987), whereby various power levels can be accessed via control functions in the part program generated. Multi-channel capabilities are therefore required so that each channel can be preset with a different power level. It is suggested that the controller needs to be able to effectively switch channels without significant delay in order to assure that no irregularities appear on the cut edge.

MODEL-BASED OPTIMISATION

A complete description of the mathematical formulation has been presented elsewhere by the authors, Di Pietro and Yao (1995a). Additionally, model-based optimisation for laser cutting when encroaching upon a boundary has been studied previously in order to assure cut quality right up to pre-cut sections (Di Pietro et al., 1995b). Results showed that process manipulation can lead to significant quality improvements. The work is therefore extended to examine the geometric case of cornering. A brief summary is given below.

The Japanese corporation Mitsubishi (Moriyasu et al., 1986), and other research groups realised early on that adaptive control of laser parameters was a real possibility with conventional CNC (computer numeric control) systems. By adapting parameters such as laser power levels, switching between continuous wave (CW) and pulsed mode, and effecting cutting speed changes, vast quality improvements were obtainable. Such techniques are trial-and-error based, and therefore are time consuming, whereby the optimal set of parameters may still not be reached. It was recognised by Biermann and Geiger (1991) that simulation of the laser process under the effects of the motion system can lead to improved results for laser processing.

An optimisation strategy is therefore proposed in which it forces the cutting front temperature to remain uniform, even when laser cutting conditions are unsteady. The problem of minimising the deviation from steady state results in a non-linear power profile, as the inter-relationships between laser parameters are complicated by the mobility exhibited by the cutting front. Uniform cutting front temperatures affect quality in various ways. They produce better quality by reducing i) kerf widening effects, ii) heat-affected zones, and iii) wide spread self-burning. At the very least, uniform cutting front temperatures reduce the variability in progressive cut quality.

The strategy developed is iterative by nature (see Fig. 1). The model proceeds forward in time by the accumulation of the timestep Δt of integration. By monitoring the status of the front temperature at every instance, a steady state value can be established.

$$| T_f^{j+1} - T_f^j | < \Delta T \qquad (1)$$

The cutting front temperature can be disturbed subsequently by a speed change of the motion system or a change in the workpiece heat accumulation (due to the workpiece geometry and the presence of the kerf and other boundaries which frustrate heat conduction). As the change in temperature exceeds the previously set limit ΔT, a course of action is required in the form of a power rise or reduction of size ΔP_{inc}.

$$\Delta P_{inc} = | T_f^{j+1} - T_f^j | \times k \qquad (2)$$

The size of this power increment is based on two pieces of information forwarded to the optimisation module. In order to return the system to its controlled state, the power change to be effected is directly proportional to the temperature deviation observed. For example, a large temperature difference results in a large power control action. This is achieved by the proportionality constant k, which effects the convergence rate of solution. Of course, if the constant is too large, then the temperature cannot be stabilised within the ΔT control limit.

Logically if the cutting front temperature rises, then a power reduction is needed to return the temperature to its previous level. By analogy, a temperature fall requires an increase in power. This conditional test is expressed as follows:

Condition:

$$\{\text{if } (T_f^{j+1} > T_f^j)\}: \quad \Delta P^j = \Delta P^j - \Delta P_{inc}$$
$$\{\text{if } (T_f^{j+1} < T_f^j)\}: \quad \Delta P^j = \Delta P^j + \Delta P_{inc} \qquad (3)$$

From which, an updated cutting front temperature is determined. If it falls within the set allowable temperature tolerance, the model then proceeds forward to the next user-specified beam position whereby the procedure repeats.

NUMERICAL ISSUES

After material is expelled from the kerf, conduction cannot occur across this region as these points are now part of the convective environment. The model accounts for this by removing all nodes above melting point which fall within the extent of the assist gas stream.

On most occasions, it is necessary to initiate a keyhole in the work material prior to cutting. This issue is considered so that a realistic cutting process is simulated. Molten material can only be ejected upwards in all directions until complete penetration. The model can be used to obtain minimum penetration times required to create such initiation holes, but to obtain more accurate penetration times, it is necessary to consider the formation of surface plasma (Yilbas et al., 1990). Once a kerf is formed, the effect of these plasma's are reduced somewhat due to the ability of the gas jet to remove them more effectively. Surface plasma's are neglected in this model as the main emphasis is to simulate the cutting process as opposed to the drilling one.

EXPERIMENTAL PROCEDURE

Experimental Setup

The experiments were performed on a fast axial flow 1.5 kW CO_2 laser (PRC model FH 1501). The beam mode is essentially TEM_{00}, with all experiments performed under continuous wave (CW) operation. The laser beam was focussed down to 250 µm through a 5" ZnSe high pressure meniscus lens. The throat diameter of the nozzle used was 1 mm, and a nozzle-standoff distance of 1 mm was maintained. Oxygen assist gas pressures were kept constant at 2.7 bar throughout the experiments, and cutting was performed on bright, cold-rolled mild steel sheet (AS 1595) of 1 mm thickness. Spectrographic analysis was carried out on the steel sheet and its metallurgical composition is given in Table 1.

Preparatory Work

Verifying Laser Beam Power Levels and Control. In order to perform the experiments, actual power levels needed to be established for accurate model validation. A Macken P - 2000C power probe was subsequently used for this task. It is a calorimeter-type power meter, which measures unfocussed laser power using a timed exposure and relies on knowing the mass of material it heats up. Stable discharge currents were observed for all of the eight resonator discharges. Current control is via a 12 bit digital word which allows accurate manipulation through part programs generated.

To achieve actual quality improvements through the model-based power optimisation strategy, it is necessary to have current or power control of the laser which can respond fast enough to closely approximate the theoretical, desired profiles. Tests were therefore performed to check the performance of the laser under rapidly changing commands.

Fig. 2 shows the response of a resonator discharge to a step input. A power change from zero to 1 kW was commanded via the controller. The signal was obtained from a BNC bulkhead receptacle located on the discharge current meter (mA). The output approximates a step response of a first-order system, and thus the time constant of the system can be evaluated. It was found that the response reached 63.2% of its total change in as little as 1.3 ms. After two time constants, the response had all but reached its final value. Thus the laser control facility was adequate to perform the optimisation power strategies to be implemented.

Verifying Motion System Accelerations. It was shown previously by the authors Di Pietro and Yao (1995a), that the characteristics of the handling system affects the dynamics of the cutting front and as a result, will affect the quality of cut possible. All simulations therefore needed to be run under accelerations and decelerations which closely resembled those possible in practice.

In order to achieve this, a TRANS-TEK 290 Series LVDT (AC-AC) was attached to the motion system. The axially displaced coil produces a change in voltage directly proportional to the displacement. After some amplification of the signal, it was fed into a data acquisition system.

Results showed that the CNC typically was capable of accelerating and decelerating at about 300mm/s^2. This is in accordance with other commercially available systems. It should be noted that such motion profiles occur whilst under interpolation or contour mode, as opposed to point to point mode where no position error checking occurs.

RESULTS AND DISCUSSION

Workpiece Temperature Distributions

In order to validate workpiece temperature distributions calculated to those determined experimentally, type K, chromel-alumel thermocouples were used. An overall diameter of 0.5 mm was chosen because thicker diameter thermocouples result in slower response times. The thermocouples were imbeded 1.5 mm out from the generated corner point along the centreline of the workpiece (see Fig. 3). Such positions were chosen to avoid high temperature gradients closer to the line of cut and as such, allows the thermocouples to respond adequately. In addition, validation becomes difficult at very close positions to the line of cut because small shifts in thermocouple location result in large variations. This is due to the large temperature gradients experienced around the interaction zone. The thermocouple positions were accurately checked using a microscope and data collection was triggered via an electrical relay in the controller which actuates the beam shutter mechanism.

Often when computer processing of thermocouple data is needed, various n-th order polynomials are fitted to data. For precise analysis of the results, the thermocouples need to be calibrated directly against a known temperature source. In our case we employed the use of an accurate industrial oven to provide the heating source. The oven was set to reach 1000 ^{o}C over a period of one hour (NABER kiln with a microprocessor based temperature program controller - Model PS - 962C). The signal output was measured every 10 ^{o}C, with consistent, repeatable values only achievable up to an oven temperature of about 870 ^{o}C. After which, random voltage fluctuations were significant. Although the thermocouples can withstand such temperatures, the voltage output from the amplifier was somewhat limited. A reasonably linear relationship was observed between temperature and signal output, but actual data was used for signal analysis instead of a curve-fitting algorithm.

Fig. 4 shows typical results obtained from model execution as compared to experimentally determined thermocouple values for laser corner cutting. Various cutting conditions are examined. It is clear from the plots that severe transience is common. Such high temperature yields about the corner point result in tip melt-off which degrades the overall quality of the finished product. Thermocouple detachment from the workpiece did occur because of the significant bulk heating experienced at this location. This explains why the temperature plots are incomplete for the very final stage of cutting. Nevertheless, numerical temperature histories are favourably compared. In all cases temperatures continually rise, even though the laser beam actually moves away from the thermocouple location after the corner point has been reached. This is because of the large heat accumulation present in the workpieces.

Fig. 5 shows typical progressive temperature contours determined from the numerical model when cornering. It is clear that heat diffusion in the workpiece is frustrated by the directional change of the kerf and results in a more complex isothermal description. Because of the higher temperatures experienced in the vicinity of the corner point when generating male corners, they are much more susceptible to tip melt-off when compared to their female counterparts. This feature is generally true under all laser corner cutting conditions.

Transient Effects

Fig. 6 shows typical simulation results when a corner is part-programmed. It is clear that the transmitted power increases to the corners because of the deceleration of one axis to zero. After the corners, greater beam coupling results because of the acceleration of the other axis to reach the target speed of 30 mm/s. Also note the dynamics of the cutting front, where there is an apparent speed lag behind the processing velocity. The net affect of these two contributions are shown by the complex temperature profiles generated. The contour change involved in processing such routines (viz., the positional relationship of existing boundaries to the kerf's altered directional path), impacts on the transmitted power, front velocity and temperature in that they do not stabilise to their pre-corner, steady-state values but to other levels.

Industry Practice for Quality Improvements

As mentioned above, many industrial laser cutting systems have facilities to adapt laser power to suit the actual cutting speed achievable around corners. If the processing speed falls, the controller attempts to reduce the laser beam power in order to maintain the rate of energy input to some degree of uniformity. This control action between speed and power is a linear one (see Fig. 7).

From Fig. 7, it is possible to derive the governing equation for such a strategy.

$$P_{inc} = (P_s - P_{thres})\,(V_b / V_s) + P_{thres} \quad (4)$$

where P_{inc} is the new calculated power level, P_s is the steady-state beam power, P_{thres} is the minimum accepted power level allowed, V_s is the steady-state processing speed, and V_b is the current, actual speed of the motion system (or beam) under accelerating conditions. If a simple power-feed ratio is assumed, then when the corner point is reached, a zero velocity condition will result in a zero power command. Therefore a minimum threshold power limit is selected in order to maintain energy levels sufficient for complete penetration cutting (Moriyasu et al., 1986). Such levels can only be determined by extensive trial-and-error experimentation.

This strategy was incorporated into the numerical model to ascertain its affect on transmitted power, cutting front mobility and temperature. Fig. 8 shows typical co-ordinated parameter control schemes used for improving cut quality. Fig. 9 then shows the effect of these implemented strategies respectively.

From the results, it is clear that such linear adaptive control schemes produce complex effects on the cutting front. No linear power manipulation can bring about an optimised cutting front temperature when cornering. Accelerations imposed on the process significantly effect the mobility of the cutting front, and hence beam coupling levels are altered in a non-linear fashion.

Power Manipulation for Quality Improvements via the Model-based Optimisation Strategy

The above strategy outlined for assuring quality around corners intuitively makes sense. That is, control the rate of heat input into the cutting zone to achieve a more stable process. The simple fact that operators usually repeat many trial-and-error experiments in order to account for discrepancies in the above strategy, clearly supports the fact then that there is not a one-to-one correlation of laser power to cutting speed.

The model-based power optimisation strategy is therefore appropriate for cornering (as well as for many other geometric routines). It can force cutting front temperatures to remain uniform right around completely generated corners. It is expected that controlled temperature levels about the corner tip will reduce melt-off considerably. Fig. 10 shows power profiles determined by the scheme for various cutting conditions.

Fig.'s 11 and 12 show typical results when the optimisation strategy was physically implemented when cornering. The samples were mounted in bakelite and then polished (diamond polisher and paste). They were subsequently ultrasonically cleaned with acetone and Freon-113, whereby they were finally prepared for microscopy by gold coating the top surfaces to eliminate impurity leakage under vacuum conditions. It is clear that corner melt-off is significantly reduced by adapting laser power in a non-linear fashion as determined by the optimisation module. So much so, that minimal kerf widening can be discerned even when viewed under high magnification.

It must be stressed that although industry practices may produce similar results by using linear power-feed assumptions, they require iterative, time consuming trial-and-error experimentation whereby fine parameter tuning can at best lead to a reasonable approximation. In contrast, model-based optimisation leads directly to an optimal solution from a single-step model execution.

CONCLUDING REMARKS

Results show that by appropriate parameter control, corner melt-off can be greatly reduced. Such a model-based optimisation strategy stabilises cutting front temperatures right around corners, where ordinarily tip temperatures rise markedly due to the accelerations imposed on the process. Visual examination of the laser cuts show that kerf widening is almost completely eliminated. This strongly suggests that the energy balance at the interaction zone is kept at an equilibrium. Apart from significant quality improvements possible through this strategy, model-based optimisation eliminates current industry practice trial-and-error experimentation and leads directly to an optimal solution.

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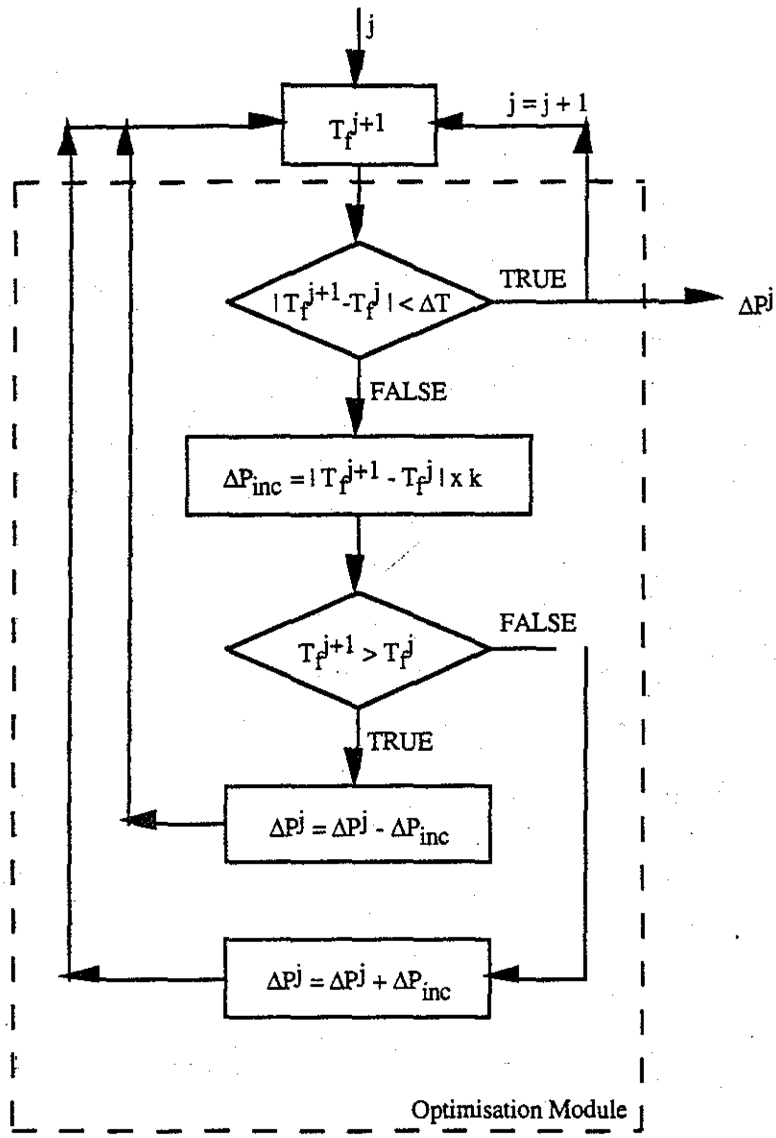


Fig. 1 Power optimisation strategy for cutting front temperature stabilisation

Table 1. Spectrographic analysis of AS 1595 (1 mm)

Percentage composition by mass

% C	% Si	% S	% P	% Mn	% Ni	% Cr	% Mo	% V	% Cu	% W	% Ti
.0572	.0081	.0124	.0100	.2538	.0210	.0056	.0039	.0012	.0082	.0035	.0011

% Sn	% Al	% B	% Nb	% Fe
.0118	.0590	.0000	.0000	99.543

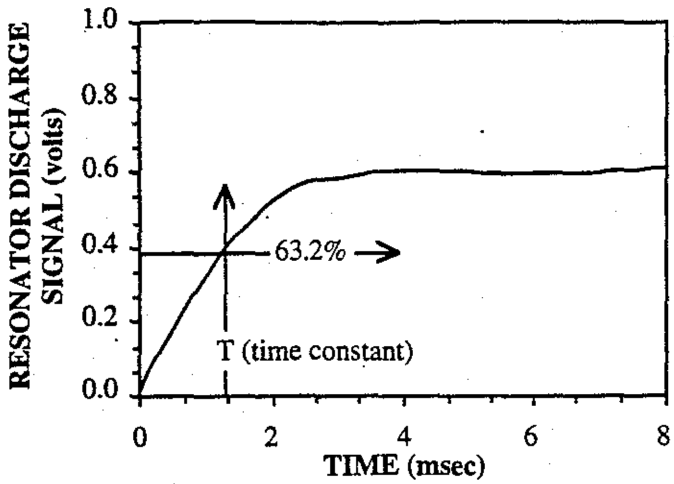


Fig. 2 Response curve of the discharge current subjected to a large step input from zero beam power to 1 kW

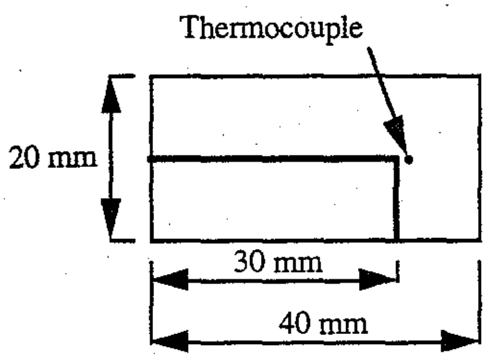


Fig. 3 Workpiece dimensions and thermocouple location when corner cutting

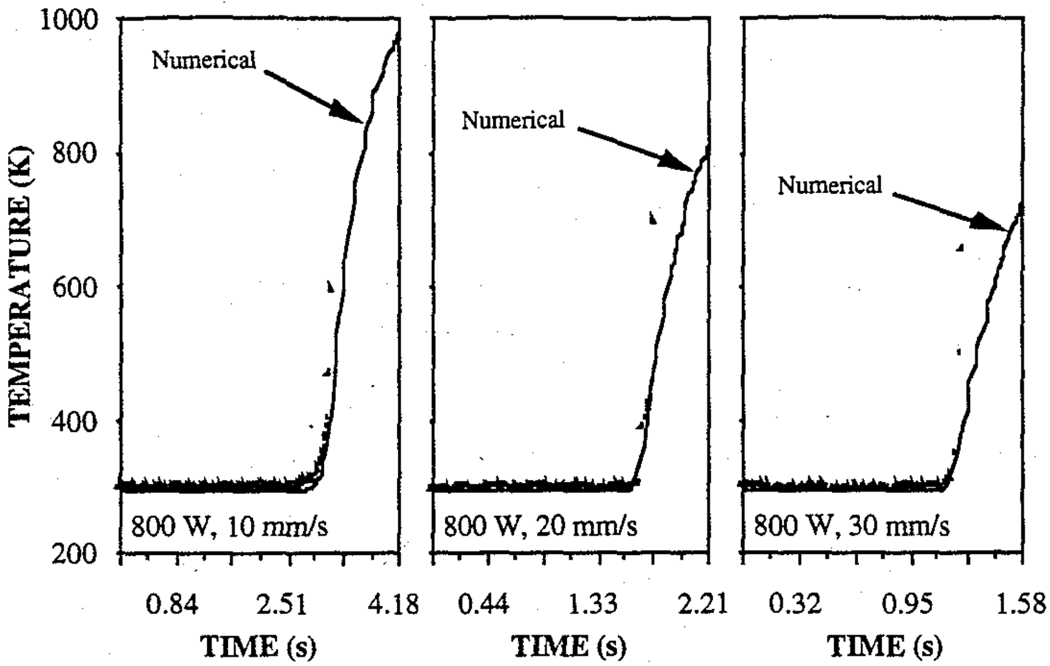


Fig. 4 Typical cornering temperature measurements (obtained by thermocouples) as compared to simulation results

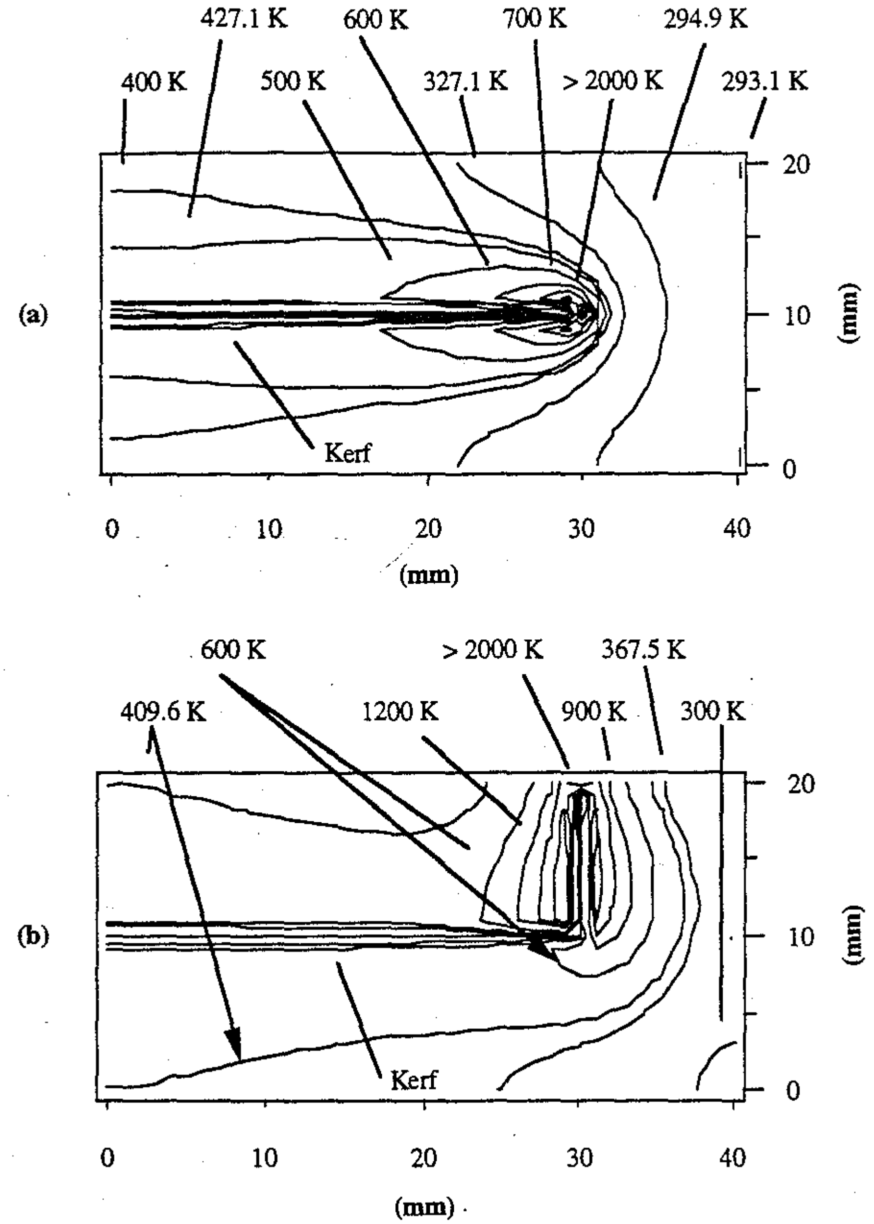


Fig. 5 Progressive numerical temperature contour plots at a) 3.075 s, and b) 4.125 s (laser power: 800 W, cutting speed: 10 mm/s)

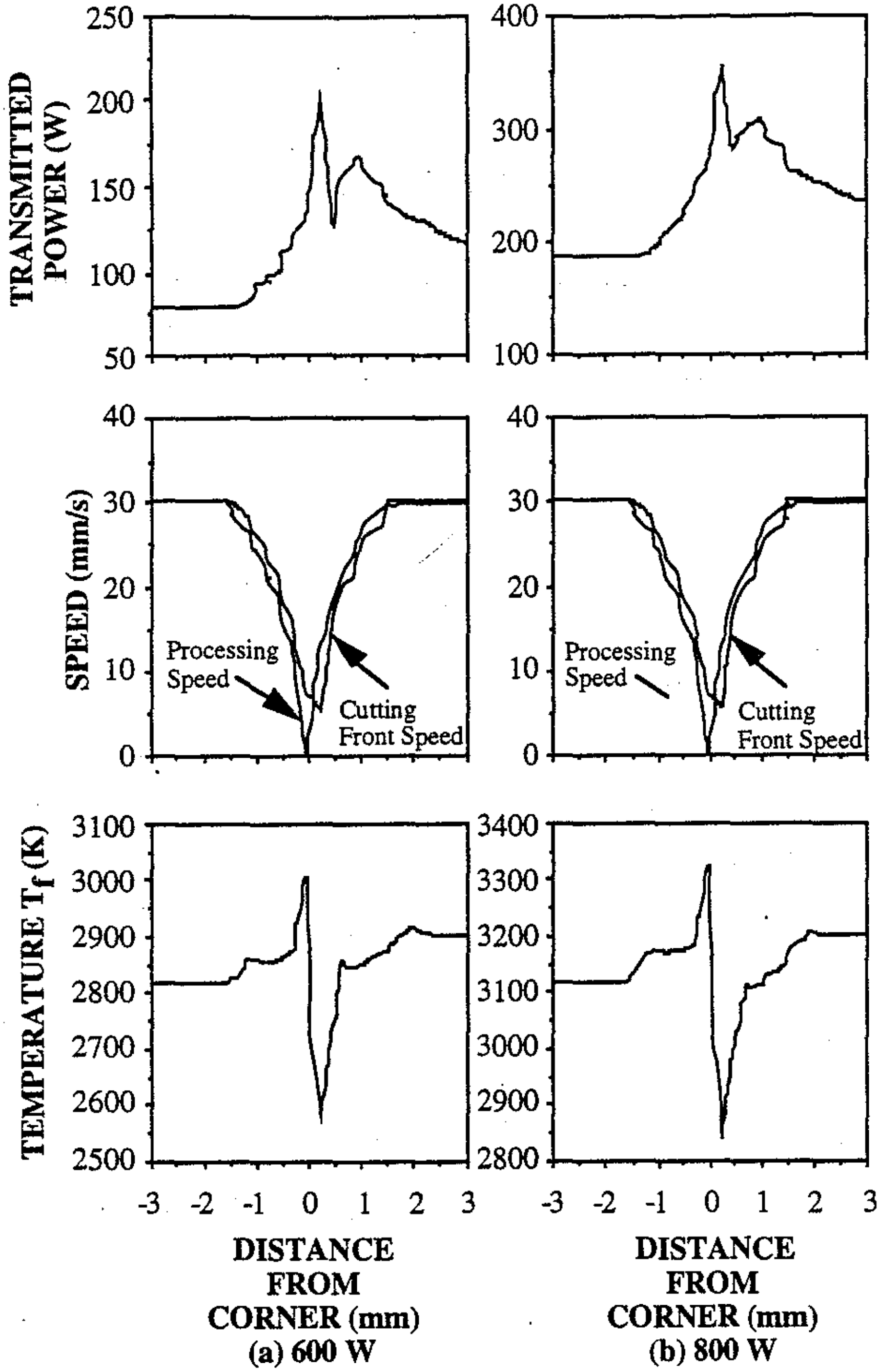


Fig. 6 The effect of cornering on transmitted power, front mobility, and cutting front temperature (cutting speed: 30 mm/s)

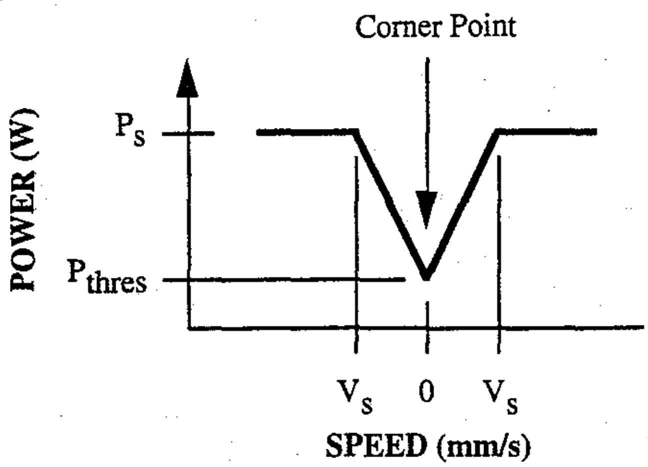


Fig. 7 A common power manipulation strategy for quality improvements when cornering

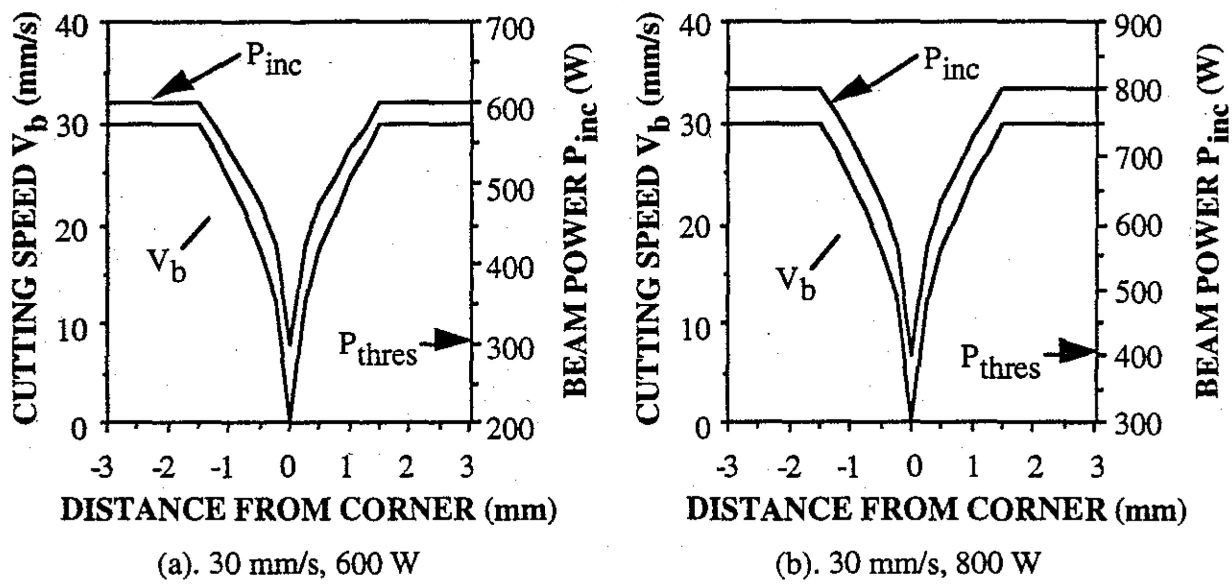


Fig. 8 Typical co-ordinated parameter control schemes used for improving cut quality

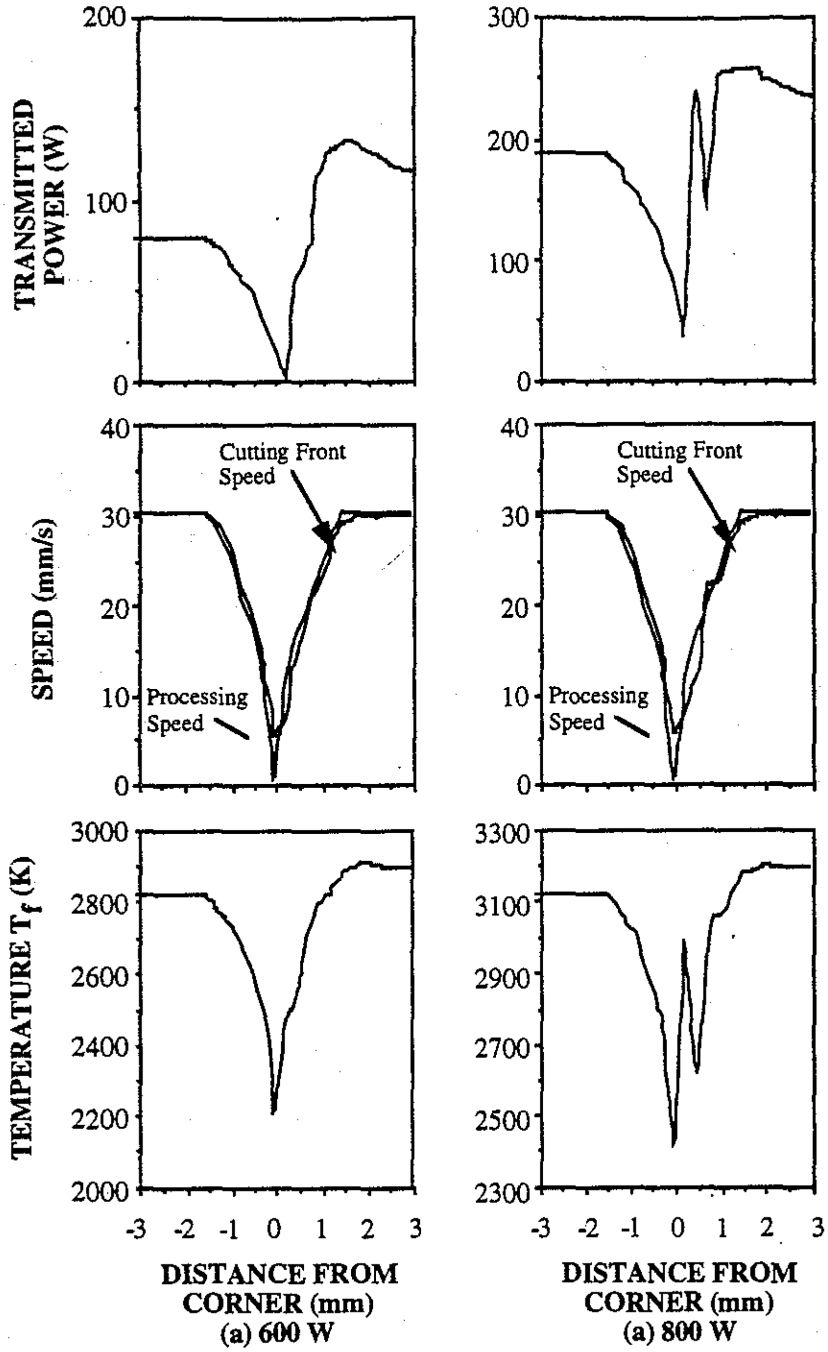


Fig. 9 The effect of linear power ramping when cornering on transmitted power, front mobility, and cutting front temperature when the threshold power is a) 300 W b) 400 W

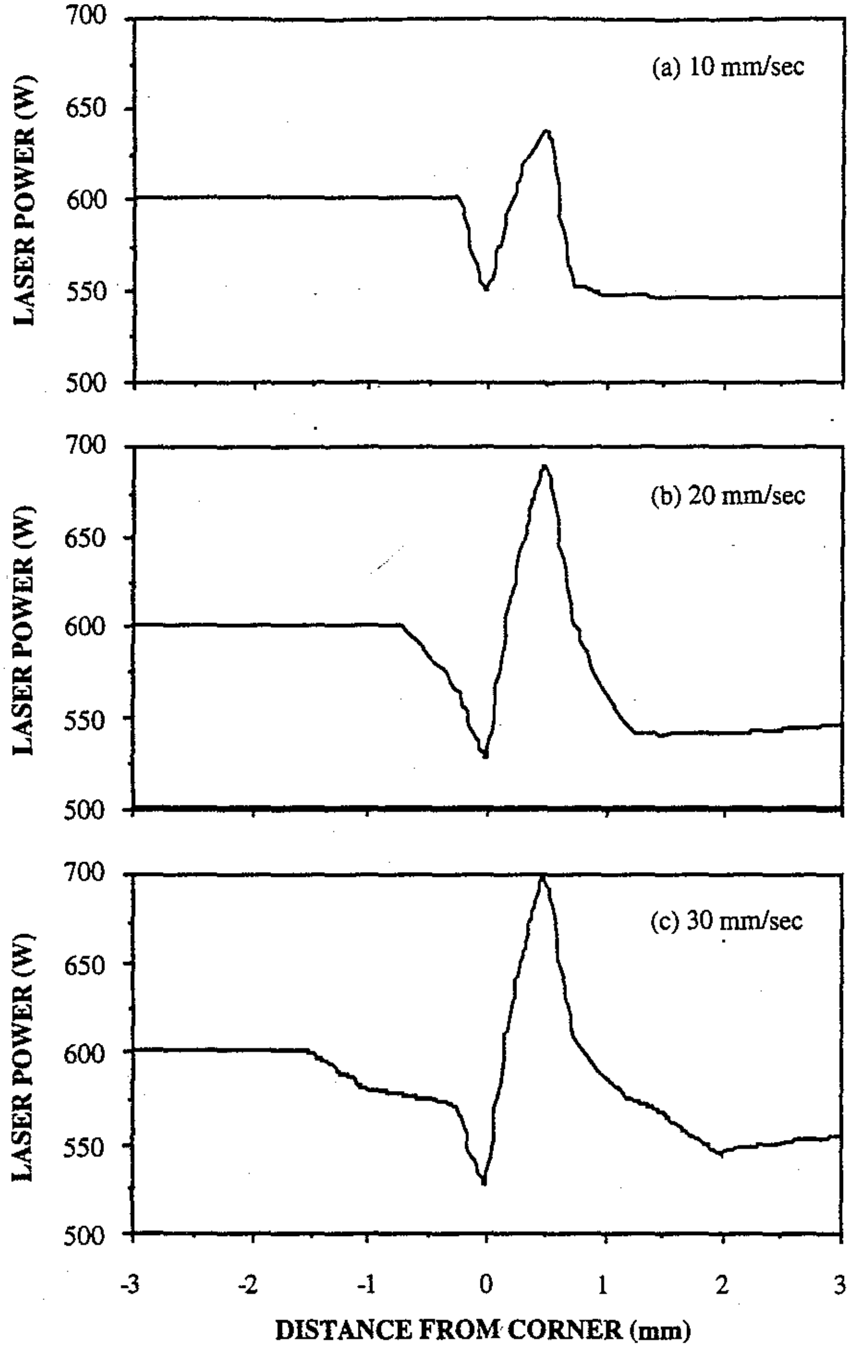
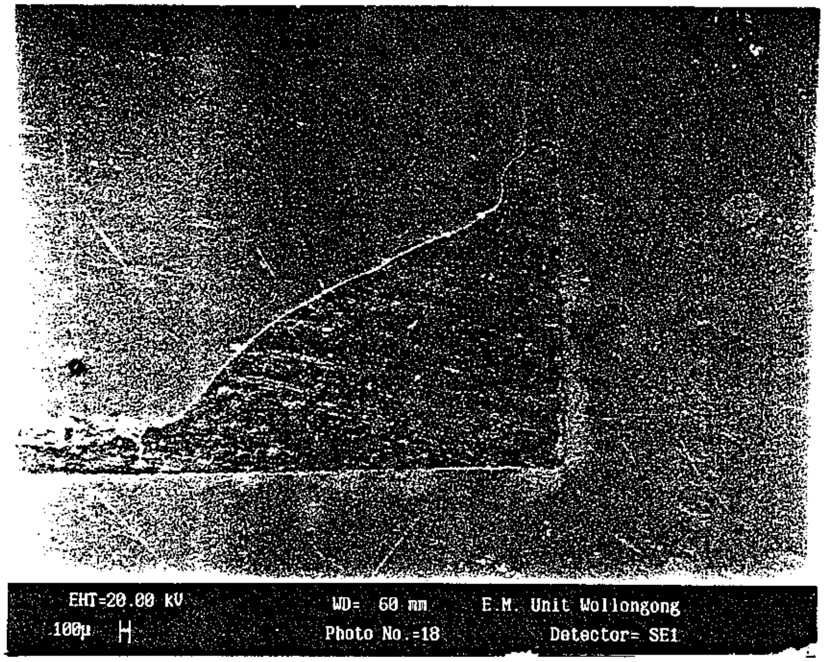
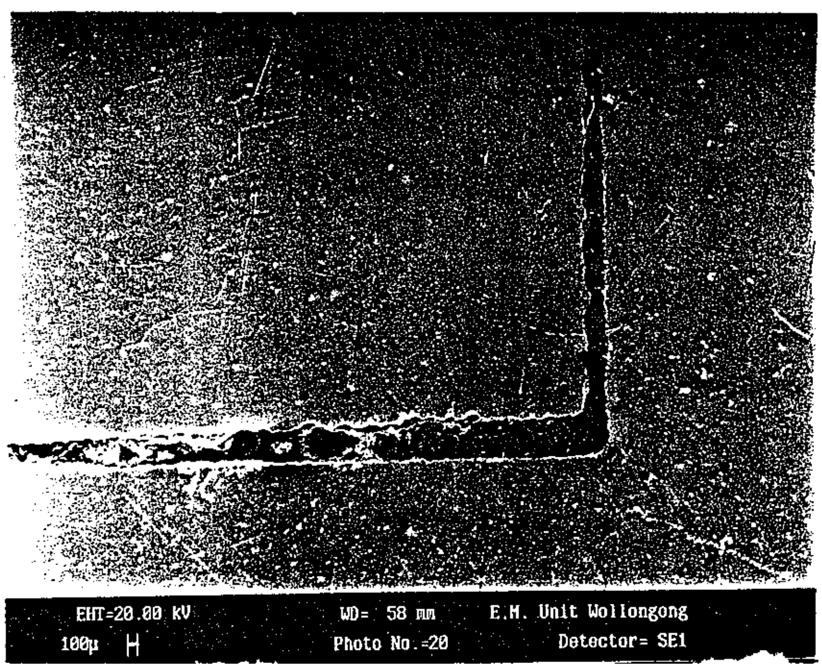


Fig. 10 Laser beam power profiles required for temperature stabilisation when cornering (initial laser power: 600 W)

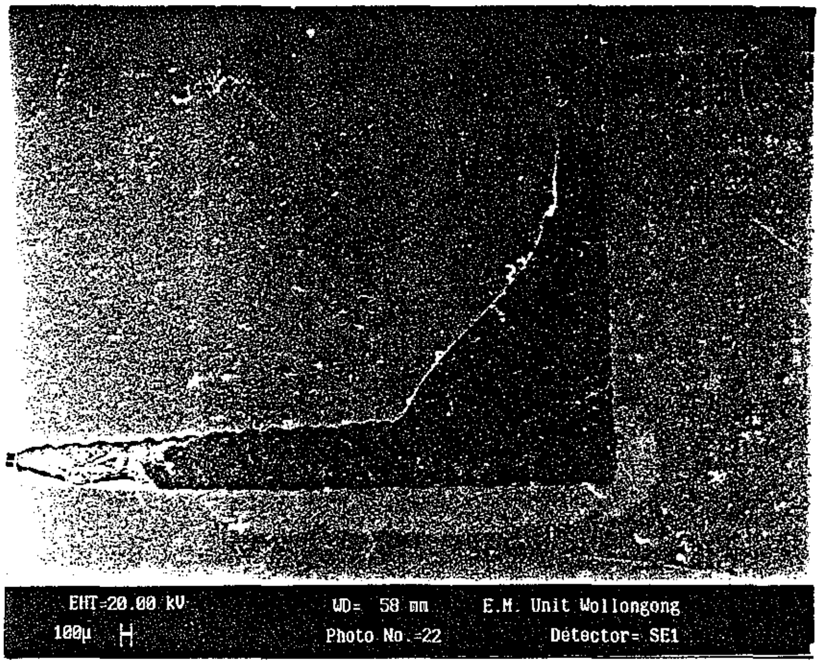


(a). Laser cutting without power optimisation



(b). Laser cutting with power optimisation

Fig. 11 SEM micrographs comparing obtainable quality with and without laser power adaption (laser power: 600 W, cutting speed: 20 mm/s)



(a). Laser cutting without power optimisation

(b). Laser cutting with power optimisation

Fig. 12 SEM micrographs comparing obtainable quality with and without laser power adaption (laser power: 800 W, cutting speed: 30 mm/s)