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Abstract

Most laser cutting systems utilise a gas jet to remove molten or vaporised material from the kerf. The speed, economy and quality of the cut can be strongly dependent on the aerodynamic conditions created by the nozzle, workpiece proximity and kerf shape. Adverse conditions can be established that may lead to an unwelcome lack of reproducibility of cut quality.

Relatively low gas nozzle pressures can result in supersonic flow in the jet with its associated shock fronts. When the nozzle is placed at conventional distances (1-2mm) above the workpiece, the force exerted by the gas on the workpiece and the cut products (the cutting pressure) can be significantly less than the nozzle pressure. Higher cutting pressures can be achieved by increasing the height of the nozzle above the workpiece, to a more damage resistant zone, provided that the shock structure of the jet is taken into account. Conventional conical nozzles with circular exits can be operated with conditions that will result in cutting pressures up to 3 Bar (g) in the more distant zone. At higher pressures in circular tipped nozzles the cutting pressure in this zone decays to inadequate levels. Investigations of a large number of non-circular nozzle tip shapes have resulted in the selection of a few specific shapes that can provide cutting pressures in excess of 6 Bar(g) at distances of 4 to 7mm from the nozzle tip.

Since there is a strong correlation between cutting pressure and the speed and quality of laser cutting, the paper describes the aerodynamic requirements for achieving the above effects and reports the cutting results arising from the different nozzle designs and conditions. The results of the work of other investigators, who report anomalous laser cutting results, will be examined and reviewed in the light of the above work.

Introduction

The cutting of sheet materials with a CW CO_2 laser was probably the first and most widely accepted application of a laser as an industrial machine tool. It has been demonstrated to provide an economical and reliable production process. Some systems, in the hands of experienced and skilful operators, have given many years of reliable service. However there are a number of examples of more demanding applications, such as limited penetration or precision control of kerf width and shape, where the required performance is obtained with disappointing infrequency. Understandably, the failures are not reported widely in public but are probably the subject of much board-room discussion.

Laser cutting is essentially an automated process and cannot rely on operator skills for real-time process control. In common with many industrial operations, it is a process where the qualities of the product are controlled by the values and interactions of many variables (factors). A graphic display of many of the input factors which could influence laser cut quality is given in Figure 1. Since the process can be used for many applications, the judgement of cut quality will be dependent on a combination of the values of a number of features or output factors of the process.

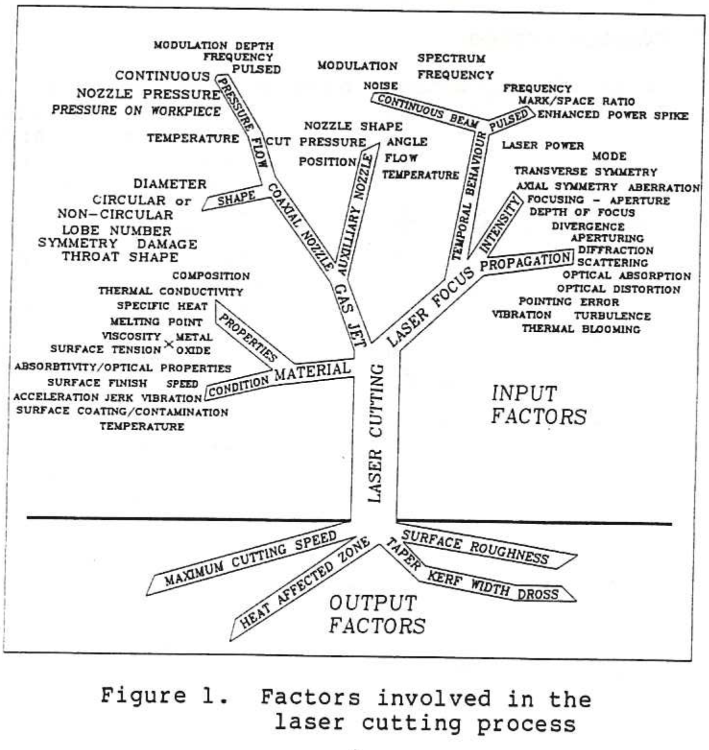

Figure 1. Factors involved in the laser cutting process

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Automated process quality control could be employed if it was possible to identify, without ambiguity, a small number of independent factors whose variation was solely responsible for the detected deviation in quality. This is the case with only a few industrial processes. In general there are so many non-linear, interacting input factors for a process that it would be impractical to devise all the algorithms necessary for quality control. It is felt that one solution is the identification of the dominant factors whose variation could lead to discontinuous changes in process output. This could then be followed by the selection and maintenance of working points for the input factors that avoid areas where strong non-linearities are known to exist. This approach implies that instrumentation is required for the monitoring and control of the relevant factors. Unfortunately, instrumentation for real-time monitoring of some of the more important factors has only recently become available so that, in spite of the publication of much laser cutting data, the experimental conditions and values of many of the process input factors are recorded infrequently.

The current work has been designed to identify the more crucial factors in laser cutting which exhibit a non-linear or discontinuous influence on the product. The aim is to increase the repeatability of the process to permit greater precision and reliability for nuclear engineering applications. One subsidiary requirement has been for an improvement in the resistance of nozzles to damage by the cutting process.

Aerodynamic aspects of laser cutting

Gas assisted material cutting with a CO_2 laser is performed by focusing the beam near the surface of the workpiece while removing simultaneously the molten or decomposed products with a jet of gas aimed at the interaction point. The jet can be formed by a nozzle, co-axial with the axis of the laser beam or by an off-axis auxiliary nozzle. The co-axial nozzle has the advantage of providing some protection for the beam focusing optics against damage by ejected cutting debris or other environmental contaminants.

The gas used in the jet can be inert to protect the workpiece from oxidation or contamination. Alternatively, an active gas may be used to assist the cutting process with additional exothermic energy.

The efficiency with which the gas performs its required function is influenced strongly by the aerodynamic conditions existing both in the impinging jet and in the flow of the assisting gas and the arising cutting vapours in the slot or kerf of the cut. The dominant requirement of the gas flow is the coupling and transfer of its momentum to the liquid surface and the debris. The gas flow and its interaction with the liquid is complex and much investigation is required before it is possible to describe the influence and consequences of gas jet conditions more fully.

Current practice

A number of authors have described and discussed the design of nozzles used for laser cutting [1-8]. Diagrams of some of the designs discussed are shown in Figure 2. Most installations appear to use Designs b,c or d. A number of users employ the flat-tipped design (f) but care should be exercised in the choice of nozzle gap (q.v.). There is some contradiction and confusion generated by the reported observations but most of the authors agree that not only does "the nozzle shape and its gas flow characteristics play an important role in the laser cutting process", but also that setting and alignment requires precision.

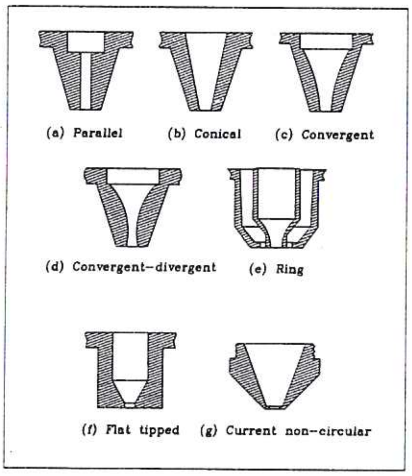


Figure 2. Commonly used co-axial gas nozzles

It appears that the most accepted condition of use of a gas jet is with low, subsonic jets (q.v.) from a co-axial nozzle close to the workpiece (0.3-1.3mm nozzle gap or stand-off distance). A number of attempts have been made to extend cutting performance to higher pressures but again there appears to be agreement [2-4] that high pressure, while promising higher cutting speeds and quality, does not ensure process repeatability.

Gas flow

A simplified view of a cutting nozzle consists of a reservoir maintained at constant pressure P_n (bar absolute) with a gas which expands through a throat into ambient pressure P_a. The flow rate of the gas through a throat with a circular cross-section, diameter d (mm), is [9]:

$$v = 8.2\ d^2.P_n \quad sl/min \qquad \text{for } P_n/P_a>1.89 \qquad (1)$$

During laser cutting this flow transfers momentum to the liquid metal and ejects it from the kerf. The total or stagnation pressure in the flowing gas is the sum of the local static and dynamic pressures. When the jet impinges normally on a barrier the pressure experienced by the surface is closely related to the local stagnation pressure. This will be referred to as the workpiece or cutting pressure P_c.

If the flow in the jet and nozzle is approximately isentropic (as in a subsonic jet) then the cutting pressure is nearly equal to the stagnation pressure in the nozzle reservoir. The effective cutting pressure decreases only slowly with distance from the nozzle tip (eg. only ≈15% less than nozzle pressure at a nozzle gap of 10mm). However, since the jet direction is very sensitive to manufacturing imperfection or tip damage, the subsonic jet tends to be used with small gaps.

<u>Supersonic jets</u>

When the flow becomes supersonic and a shock forms in the jet, the conditions are no longer isentropic. Flow across a shock shows a discontinuous increase in the temperature, density and static pressure of the gas and a decrease in the velocity and stagnation (total) pressure. The magnitude of these steps depend on the angle between the shock and flow direction and show a maxima for normal shocks. It is reasonable to expect that there will be a discontinuous change in the cut-assisting capability of the gas jet when this occurs.

The gas flow in the jet will become supersonic when:

$$\frac{P_n}{P_a} \geqslant \left\{1 + \frac{1}{n}\right\}^{\left(1 + \frac{n}{2}\right)} = \left\{\frac{2}{1 + \gamma}\right\}^{\left(\frac{\gamma}{1 - \gamma}\right)} \qquad (2)$$

where n is the number of degrees of freedom of the gas molecules (5 for Air, O_2 etc.) and γ is the specific heat ratio. Note that this expression is independent of the diameter of the nozzle tip and, in practice, means that detectable variations in cutting pressure occur when P, > 1.4 bar g (20 psig) [10,11].

At modest nozzle pressures ($P_n/P_a \approx 2$) a conical converging shock is formed near the exit of a nozzle throat. This shock can intersect at the axis and reflect at the jet boundary a number of times to form the characteristic Prandtl waves [12] (Figures 3 & 4).

At higher pressure ratios the converging shock becomes curved and too strong to allow regular intersection. In this case a normal Mach shock disk (MSD) is formed (Figure 5). When a jet with these characteristics impinges on a workpiece the slipstream and radially diverging flow can form a stable vortex ring on the surface (Figure 6). It is suggested that a jet that produces a MSD and associated vortex ring could result in some undesirable cutting characteristics.

These effects and their investigation are described in greater detail elsewhere [10,11].

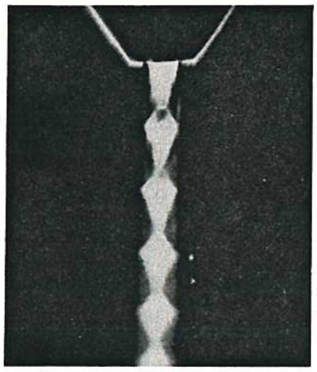


Figure 3. Schlieren photograph of waves in a supersonic jet

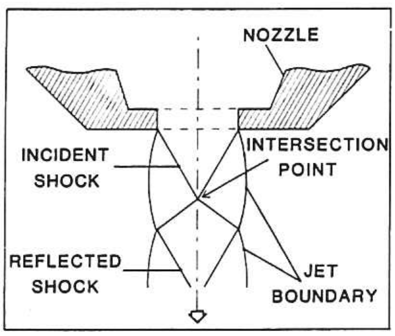


Figure 4. Regular intersection of the incident shock cone

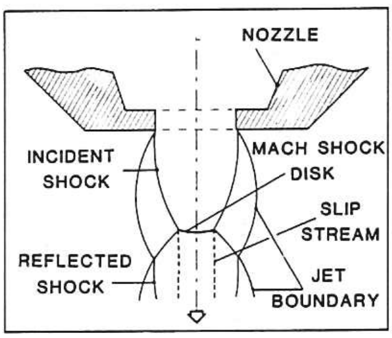


Figure 5. Mach shock disk truncating the cone

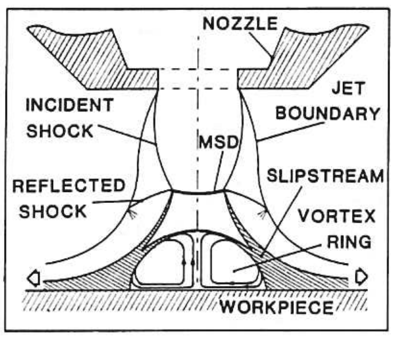


Figure 6. Impinging jet with MSD forming a vortex ring

Aerodynamic performance of nozzles

Measurements of effective cutting pressure have been made with a metal disk simulating the workpiece and containing a 0.5mm diameter hole and pressure transducer. The disk probe can be scanned along and transverse to the jet axis. The scanning pattern, data acquisition and presentation can be assisted by a microcomputer. Interpretation of the data has been aided by the observation of Schlieren images.

<u>Circular nozzle exit.</u> Figure 7 shows the variation of the cutting pressure Pc as a function of nozzle pressure and nozzle gap Z when the probe disk is scanned along the axis of the jet.

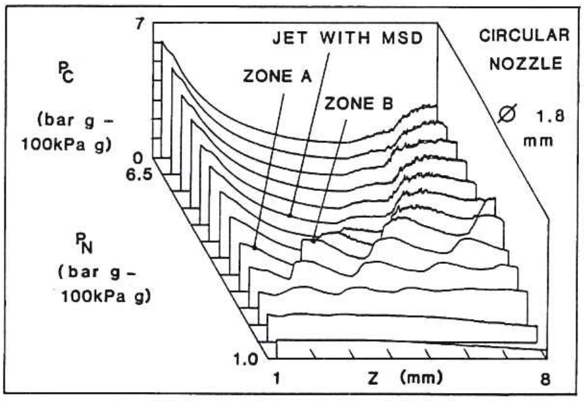


Figure 7. Variation of cutting pressure from a nozzle with a circular exit

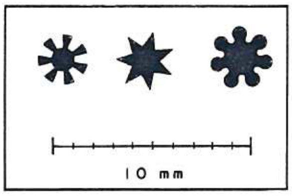
There are a number of areas of operation where the various dominant phenomena can be identified. In Zone A the cutting pressure decreases with increasing distance Z. This is caused by a strengthening normal shock near the surface of the workpiece which would not exist in the corresponding free jet. When $2 < P_n < 4$bar, the diameter of this shock, which truncates the oblique shock cone, decreases with distance until it is possible for regular intersection to occur (cf Figure 4). At this distance there is a sudden rise in cutting pressure to form Zone B. The intersecting conical shock can diverge and reflect from the turbulent jet boundary to form high pressure regions similar to Zone B at larger distances from the nozzle. The positions of these pressure maxima are a function of the nozzle throat diameter and reservoir pressure. Empirical formulae for their positions have been derived [11].

At nozzle pressures above 4 bar (for normal laser nozzle diameters) the shock disk above the workpiece no longer decays to a point but remains with a finite diameter equal to the size of the MSD in the corresponding free jet (Figure 5). In this case, there is no sudden rise in cutting pressure and Zone B is not formed. It is concluded that if a free jet can form a MSD then it is likely to form a vortex ring on a workpiece surface. In this case, high cutting pressures will only be achieved in Zone A, close to the nozzle exit.

Earlier laser cutting trials with supersonic jets from nozzles with circular throats [11] have suggested that it is possible to achieve high cutting speeds with the nozzle placed at a large and industrially attractive nozzle gap. MSD formation limits the maximum Zone B cutting pressure to <3.5 bar (50 psig). The results suggested that higher cutting speeds could be achieved at higher cutting pressures. In this case, enhanced cutting performance might be expected from a nozzle that could produce a supersonic jet without a MSD.

<u>Non-circular nozzle exits</u>. Some non-circular nozzle exits (referred to as lobed nozzles) can create a free jet with an initial shock structure in which a MSD cannot exist until high nozzle pressures are reached. A large number (34) of exit shapes have been produced and their aerodynamic performance assessed with the aim of selecting a design that will form a Zone B with a high cutting pressure [10,13].

Figure 8. Successful lobed nozzle designs



Three shapes have been found that satisfy the above aims (Figure 8). Figure 9 shows the axial pressure distribution from the star shaped nozzle. It can be seen that Zone B exists to pressures significantly higher (5-6 bar g) than those created by a circular nozzle (3.5 bar g, Figure 7). Figure 10 is a Schlieren photograph of the jet from a lobed nozzle creating a high cutting pressure. Figure 11 is the same nozzle operating at a slightly smaller nozzle gap and creating a MSD with a vortex ring and correspondingly low cutting pressure.

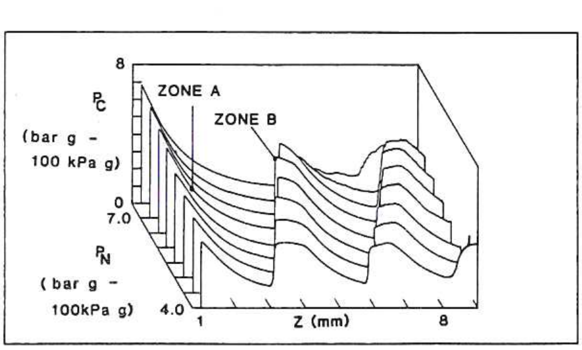


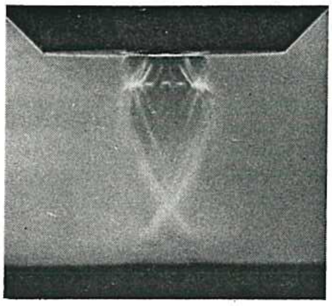
Figure 9. Cutting pressure from a star lobed nozzle

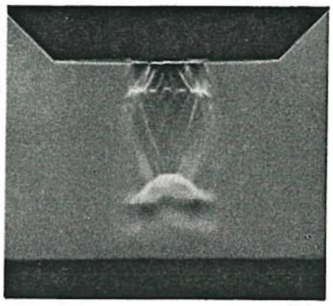
<u>Cutting pressure profiles</u> The cutting pressure profiles experienced by the workpiece simulating disk have been obtained by recording the pressure distributions in a meridional plane at a series

of discrete value of the nozzle gap Z. These can be drawn as shown in Figures 12 & 13 to give isometric representations of the effective cutting jets from circular and lobed nozzles. These distributions and their associated transverse profiles (inset) are sensitive indicators of the condition of a nozzle and suggest a simple technique for detecting the onset of nozzle damage [11].

Figure 10 (near right) Schlieren photograph of lobed nozzle with high pressure on workpiece in zone B

Figure 11 (far right) As figure 10 but with MSD and vortex ring on workpiece





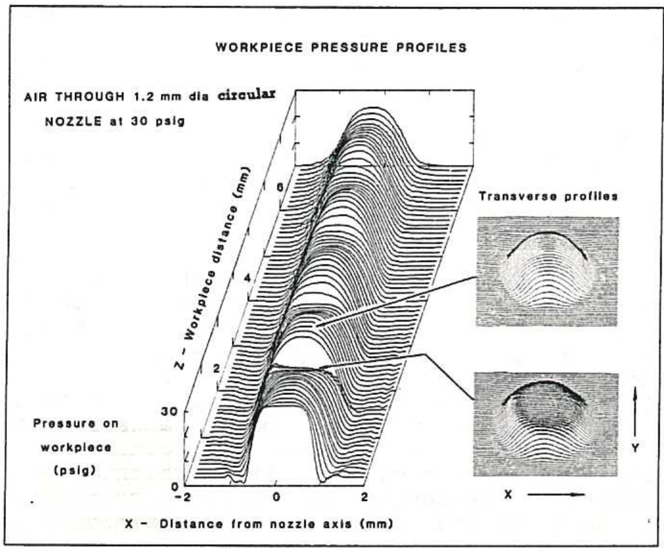


Figure 12. P-X-Z pressure profile of jet from a circular exit nozzle.

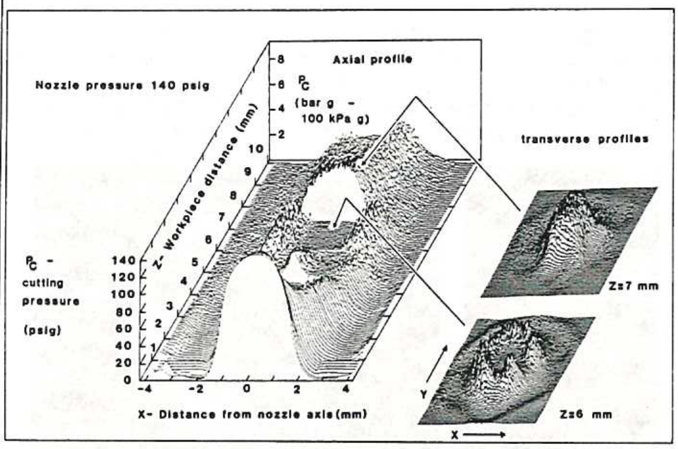


Figure 13. P-X-Z pressure profile of jet from a lobed nozzle.

Flat-tipped nozzles The nozzles cones used for the current investigations into the effects of a lobed throat, have a large diameter (≃10mm) plane exit face (Figure 2g) . A transverse scan of the cutting pressure performed close to this face (0.25mm) revealed the interesting profile shown in Figure 14. The depression around the central jet indicates that the cutting pressure close to a flat-tipped nozzle (such as that shown in Figure 2f) can become less than the ambient pressure. Integration of the pressure over the distribution shown in Figure 14 results in a nett negative pressure of > 0.07 bar (1 psig).

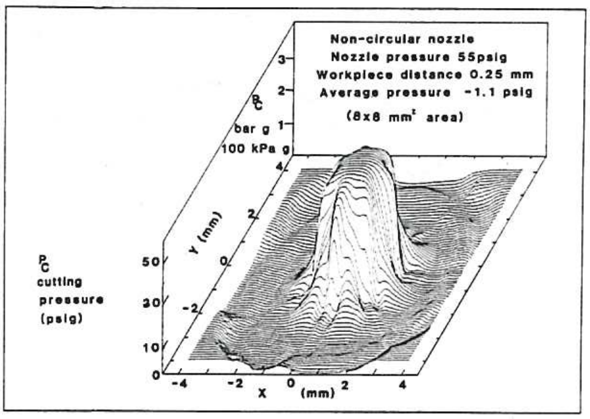


Figure 14. P-X-Y pressure profile close to the flat end of a lobed nozzle

The above phenomenon is actively exploited in other industrial nozzle applications [14]. It is caused by supersonic flow occurring at the transition from axial to radial flow when the gas escapes through the small gap between the nozzle tip and the workpiece. Radial flow causes rapid expansion of the gas with a consequent drop in static pressure.

It is suggested that this effect could have an adverse influence on laser cutting performance when nozzles with a significant "flat tip" are used at pressures >1.4 bar g (20 psig) with small nozzle gap [3,5,6]. It is possible that molten metal, which commences ejection when under the influence of the high pressure region in the centre of the jet, will still be present when the suction portion passes over it. Such adverse pressures and flow has apparently been observed in independent simulation experiments [8,15].

Cutting performance of supersonic jets

An initial comparison between circular and lobed nozzles has been made by performing a number of cutting trials. The laser used for the trials is an Electrox M1000 fast-axial flow CO_2 laser. The low-order mode beam was passed through a beam telescope to adjust the beam diameter and permit the 200mm focal length lens to be operated at an aperture of f/8. The ZnSe lens has an edge thickness sufficient to permit operation with nozzle pressures up to 10 bar. The total beam path between the laser and focusing head was 10.7 meters and the power delivered to the workpiece was ~850W.

Cutting was performed by moving optics over a vertical workpiece on the up-stroke. The maximum cutting speed was estimated by the measurement of the cut length when the linear slide was driven by a programmable controller with a uniform acceleration. The use of a ramped cut speed permitted rapid accumulation of a large amount of data.

The cuts were performed on three thicknesses of material: 1.6mm & 2.6mm PE16 (a 34/44/17 Fe/Ni/Cr alloy used in nuclear engineering) and 5.0mm 18/9/1 stainless steel. The gas used for these cutting trials was dry air and the focus was placed 0.5mm below the workpiece surface.

Tool-setting Two effective techniques have been developed to ensure accurate and repeatable setting of some of the important input factors of the process. These factors are the transverse position of laser focus with respect to the jet and the effective cutting pressure on the workpiece. The techniques also perform a useful inspection function since they are capable of alerting the operator to nozzle damage.

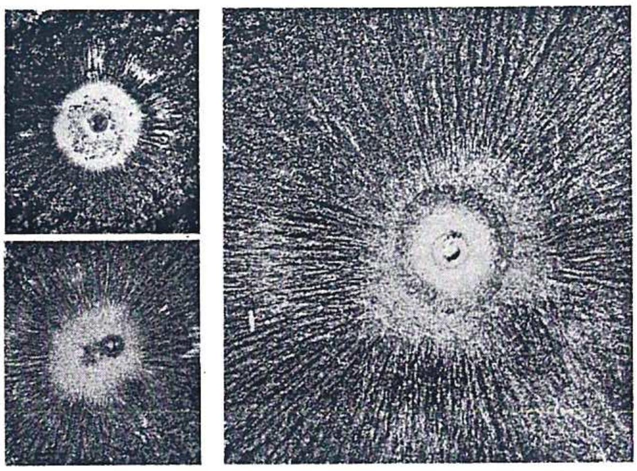


Figure 15. Black grease marks used for centering the focus within the jet (marks from a decentered jet on left)

The centering of the focus within the nozzle is achieved by marking the position of the laser focus on the workpiece with a short laser pulse (supported by low pressure gas flow). A smear of black pigmented thick grease is then placed over the focal position. Raising the nozzle to its operating pressure for a one second pulsed flow causes the grease to be displaced and leave a pattern which clearly identifies the centre of the jet. Photographs of centered and de-centered focus marks are shown in Figure 15. The use of a suitable viewing magnifier permits estimation of centering to <0.05mm (nozzle decentering tolerance is <0.1mm). The presence of anomalous streaks in a grease mark reveals the results of nozzle damage sufficient to influence the gas flow.

The cutting pressure setting technique consists of laser-drilling a hole in a firmly clamped workpiece followed by attachment of a coupling union and pressure gauge to the under-side of the sheet (Figure 16). Observation of the gauge pressure as a function of the nozzle pressure reveals the location of Zone B and permits setting of the cutting pressure to a repeatable value. Anomalous variations in the required nozzle pressure can again reveal nozzle damage. If the laser system were automated (eg. NC profiling table) transverse pressure scans could be performed as a regular inspection feature [11].

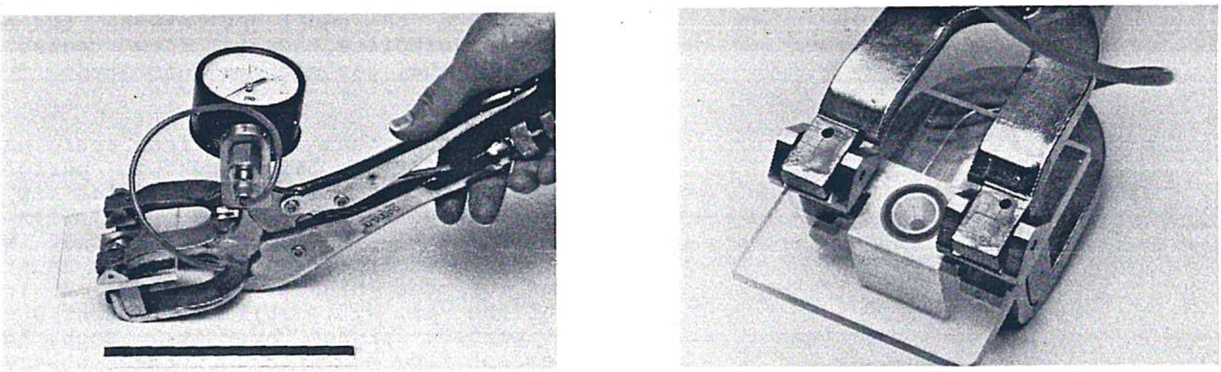


Figure 16. Hand tool used for measuring and setting cutting pressure.

Experimental cutting nozzles A number of ramped speed cuts have been performed with two nozzle types. One nozzle has a 1.5mm diameter circular exit which produces a Zone B cutting pressure of 2.9 bar (42 psig) at a nozzle gap or stand-off of 3.5mm. The second nozzle has a round lobed profile (Figure 8) and produces a maximum Zone B cutting pressure of 4.6 bar (67 psig) at a nozzle gap of 6.5mm.

Cutting trials The first cutting trials were performed with the plane of polarization of the beam perpendicular to the cut direction. The results of using the two nozzles are shown in Figures 17 & 18 together with the appropriate measurements of the cutting pressure as a function of the applied nozzle pressure. A single ramped speed cut was made at each nozzle pressure.

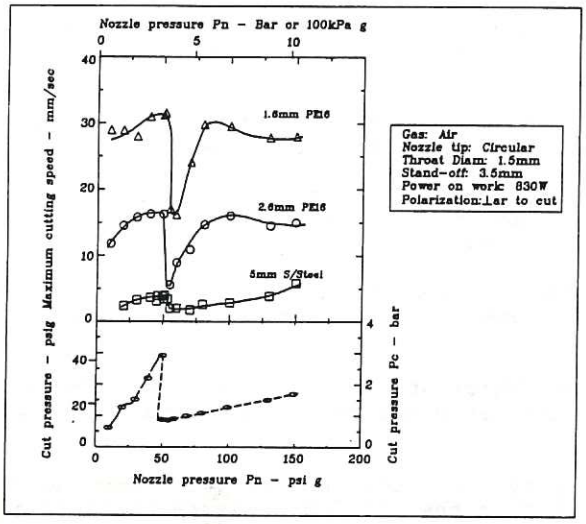


Figure 17. Maximum cutting speed from a circular nozzle (3.5mm gap, f/8 focus, polarization perpendicular to cut)

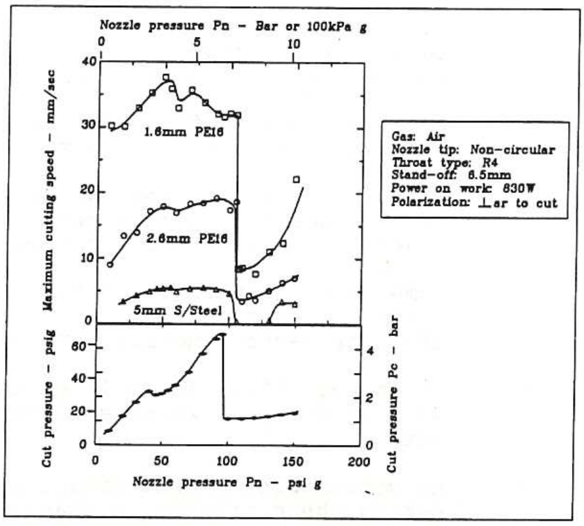


Figure 18 Maximum cutting speed from a lobed nozzle (6.5mm gap, f/8 focus, polarization perpendicular to cut)

The same trials were repeated after the equipment was re-arranged to place the plane of polarization of the beam parallel to the cut direction. The results are shown in Figures 19 and 20. The cuts performed on the 1.6mm PE16 were repeated five times in quick succession.

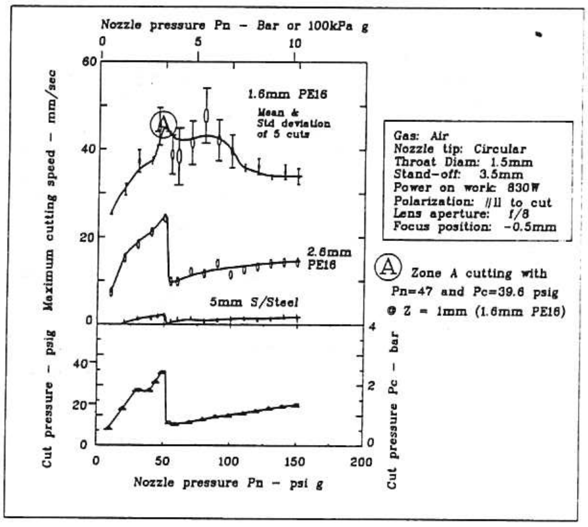


Figure 19. Maximum cutting speed from a circular nozzle (3.5 mm gap, f/8 focus, polarization parallel to cut)

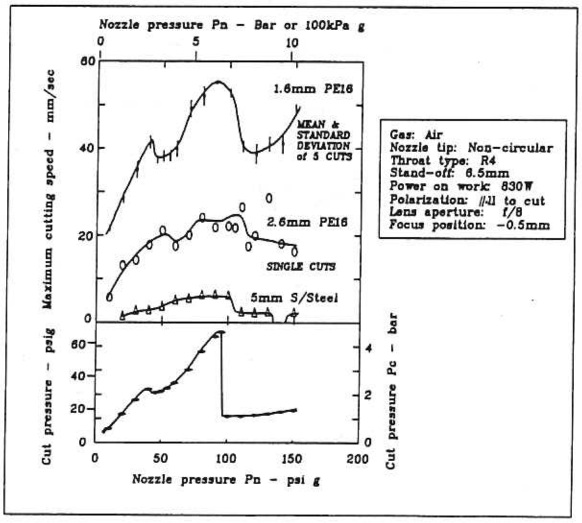


Figure 20. Maximum cutting speed from a lobed nozzle (6.5mm gap, f/8 focus, polarization parallel to cut)

Discussion

In the cutting trials efforts were made to ensure accurate alignment and pressure settin and repeatable cutting conditions. However, it was not practicable to incorporate on-lin beam monitoring so re-setting to an input factor working point could not be guaranteed. In spite of this it is possible to draw a number of conclusions from the results:-

* there is a strong positive correlation between cutting pressure and maximum cuttin speed;

* cutting speed can be enhanced by increasing nozzle pressure above that used wit subsonic flow;

* it is possible to achieve the same cutting speed from a circular nozzle working with large nozzle gap in Zone B (3.5mm) as from the same nozzle working at conventiona Zone A distances (Figure 19);

* the occurrence of a Mach shock disk, with potential for vortex formation on workpiece surface, can cause a significant reduction in cutting performance;

* supersonic flow introduces a highly non-linear relationship between cuttin performance and nozzle pressure so it is advisable to use cutting pressure as th controlled input factor rather than nozzle presure;

* some lobe patterns for the nozzle throat section are capable of creating highe cutting pressures and cutting speeds at even larger nozzle gaps (6.5mm) than circular section nozzle working in Zone B;

* it is possible, with a lobed nozzle, to cut thick stainless steel (5mm @ 6mm/sec,830W with an air jet whereas conventional techniques might resort to oxygen as the assis gas;

* no detectable nozzle damage was suffered by the lobed nozzle (at 6.5mm nozzle gap during these trials. A change was detected in the cutting pressure characteristic c the circular nozzle (operated at 3.5mm nozzle gap);

* the tolerance to nozzle gap variation in Zone B is greater than Zone A for the sam drop in cutting pressure (see Figure 21);

* many of the cuts achieved in Zone B of the lobed nozzle exhibited kerfs that wer virtually dross-free (dross height 2 Hd<0.1mm);

* the initial cutting trials show evidence of an improvement in the repeatability of th process (reduction of the standard deviation in maximum cutting speed).

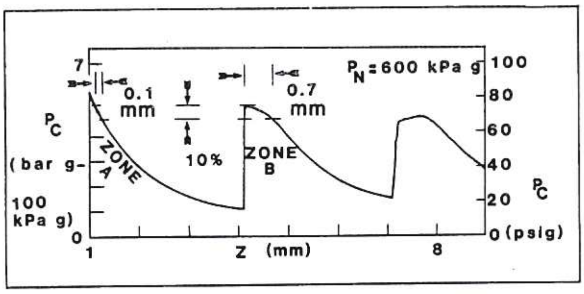


Figure 21. Non-circular nozzle gap tolerance for 10% pressure variation

It appears that the lobed nozzle can be use with advantage in a number of cuttir applications. However, its use is not withou drawbacks. The current series of nozzle design exhibit Zone B at a distance where any co-axia focusing beam from an optical aperture larger tha f/8 will result in interference between th innermost nozzle features and the beam. Thi means that the laser focus must be aligne accurately within the nozzle aperture if damage i to be avoided. This is not a practica disadvantage since the alignment accuracy require is no more stringent than that imposed by th process tolerance requirements between the focu and a jet from a conventional nozzle.

One further consequence of the use of Zone B from a lobed nozzle is the requirement fc lenses of sufficient thickness and firm mounting to permit operation with nozzle pressure in excess of 6 bar.

None of the above disadvantages apply if the nozzle is used to provide an off-axis c auxiliary cutting jet or array of jets.

Examples of applications where use of a lobed nozzle, with its large damage resistar stand-off, may provide advantages include : nuclear engineering, where the cost and delay of replacing damaged nozzles may be unacceptably large; for robot or 3d profile cuttir duties where there is limited access for conventional nozzles and a greater nozzle gap is required.

Interpretation or extrapolation of the above cutting results must be made with care. Measurements with a pressure probe, in the form of a hypodermic needle, in a kerf-like slot in a plate, show that if the cutting pressure on the workpiece surface exceeds 1.4 bar there is detectable evidence of the formation of pressure waves in the depth of the slot (Figure 22).

It is expected that these waves, whose amplitude and wavelength are a function of kerf width and cutting pressure, will have an influence on both the depth and frequency of the cut striation marks as well as dross formation. It is also expected that the degree and nature of this influence will be a function of workpiece thickness and the relative pressure and flow rates of the vapour produced by the cutting process.

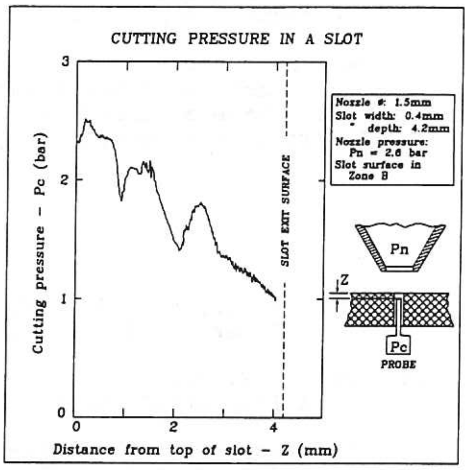


Figure 22. Cutting pressure waves in an open slot.

Conclusions

It is possible to perform gas assisted cutting of metal sheet with a CO_2 laser with a large nozzle gap (>3.5mm) at the same speeds that are achieved with the conventional small gap (0.5-1.5mm) by working with a supersonic jet. Cutting trials have demonstrated a strong positive correlation between the maximum cutting speed and the force exerted by the gas on the workpiece (cutting pressure). However, the formation of a Mach shock disk in the jet from a circular nozzle operating at pressures above 3.5 bar g reduces the available cutting pressure and consequent cutting speeds to impractically low values. It is important that the working zone for the nozzle pressure and gap are selected by direct measurement of the cutting pressure with appropriate instrumentation.

The formation of a Mach shock disk in a supersonic jet can be delayed until higher nozzle pressures by the use of a non-circular or lobed section for the throat of the nozzle. The design of the lobes has a strong influence on the performance of the jet. Current designs are capable of exerting cutting pressures up to 6.5 bar g at a nozzle gap of 6.5mm but the maximum optical aperture that can be employed in a co-axial nozzle is f/8.

The use of a lobed nozzle for cutting can result in an increase in cutting speed approaching 30% over that achieved by conventional nozzles and there is an apparent improvement in the repeatability of the process. Preliminary examination of the experimental cuts suggests that the use of a high cutting pressure improves process output quality by reducing dross, heat affected zone and kerf width.

It has been shown that the process input factors associated with the gas jet can have a significant and non-linear effect on the output. For this reason it is recommended that close attention should be given to the design, operation and maintenance of the nozzle of a cutting system. Simple tools can be devised to ensure that the appropriate input factors can be set, maintained and recorded.

It is possible that a number of the disappointing cutting performances reported when using high nozzle pressures can be attributed to adverse aerodynamic conditions [2-6]. These conditions can occur when:-

* the nozzle gap/pressure condition falls between Zones A & B and an increase in nozzle pressure causes a disproportionately low (or even negative) increase in cutting pressure and speed;

* a snub-nosed or flat-tipped nozzle is operated at a small nozzle gap and suction occurs in the annular region around the main jet.

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