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Abstract

Material cutting techniques with a focussed c/w CO_2 laser beam use a gas jet from a nozzle to assist ejection of material from the cut kerf.

Traditional techniques use a circular tipped nozzle mounted coaxial with the focussing beam. It is usual for these nozzles to be operated at low pressures (<100 kPa-gauge). Higher pressures can give higher cutting speeds but this can be associated with lack of reproducibility of cut quality. One of the reasons for the unreliable behaviour is the complex nature of the shock fronts and associated phenomena that can occur in a supersonic gas jet impinging on a workpiece.

Shocks can result in a reduction of the stagnation pressure on the surface of the workpiece. Experiments are described that demonstrate a strong correlation between the local stagnation pressure and the maximum laser cutting speed. Measurements of this cutting pressure and flow visualisation techniques have been used to investigate a number of nozzle and workpiece geometries. The formation of a strong normal shock (the Mach shock disk, MSD) in underexpanded cutting jets is found to impair cutting performance. Not only does a MSD cause a significant reduction in the cutting pressure but it can also encourage the formation of a stable stagnation bubble on the surface of the workpiece. It is suggested that the adverse flow conditions in the bubble could impede cut debris removal.

Two new nozzle designs are described whereby the formation of a MSD and stagnation bubble is prevented at normal operating pressures. Examples are given of nozzles which can exert cutting pressures in excess of 500 kPa-gauge at damage resistant stand-off distances of 4 to 7mm. The flow characteristics of nozzle designs used by other investigators is reported. These include the flat-tip nozzle, the tri-jet off-axis array and the ring or annular nozzle.

Introduction

Laser cutting of sheet metal with a c/w CO_2 laser is a complex physical process and the number of variables that determine the quality of the end product should not be underestimated [1]. An important factor is the gas jet that removes the debris and molten material from the cut kerf.

Laser cutting can be performed by focussing the laser beam near the surface of the workpiece with the simultaneous use of a coaxial or off-axis gas jet. A coaxial jet is obtained from a nozzle which is concentric with the laser beam. Figure 1 shows a collection of most commonly used coaxial nozzles.

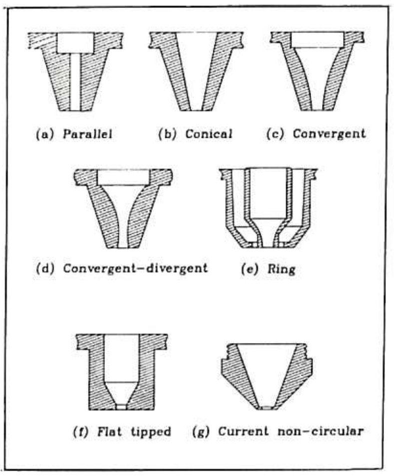


Figure 1. Commonly used coaxial nozzles.

Much data on laser cutting results using various nozzle shapes, stand-off distances and pressures have been published previously [2-9], but there appears to be little agreement on methods for obtaining a consistently high quality cut. Most authors report on cutting procedures in which the nozzle is positioned close to the workpiece (0.3-1.3mm) and with low nozzle pressures (<300 kPa-g). Experiments using higher nozzle pressures have indicated that a higher cutting speed can be reached but this does not ensure process repeatability.

A number of attempts have been made to develop a mathematical model of the laser cutting process [10,11], but the simplifications and omissions result in a poor approximation to the physical process.

It is felt that cut quality and process repeatability can be associated with the gas jet pressure that is experienced by the workpiece. The work described here was aimed at identification of the gas jet conditions that would give reliable and high quality cutting performance from a given laser system. A number of different nozzle geometries have been investigated by means of pressure measurement and schlieren flow visualisation [1,12,13].

Aerodynamic phenomena in jets from coaxial nozzles

The most important aspect of any nozzle is that the gas flow emerging from it will be supersonic if the pressure applied to it exceeds a certain value [14]

$$\frac{P_n}{P_a} > 1.89 \quad \text{(for diatomic gases)}$$

where P_n is the absolute pressure to the nozzle and P_a absolute ambient pressure. Supersonic flow from practical laser cutting nozzles is always underexpanded [15] which means that a structure of shocks is present in the jet.

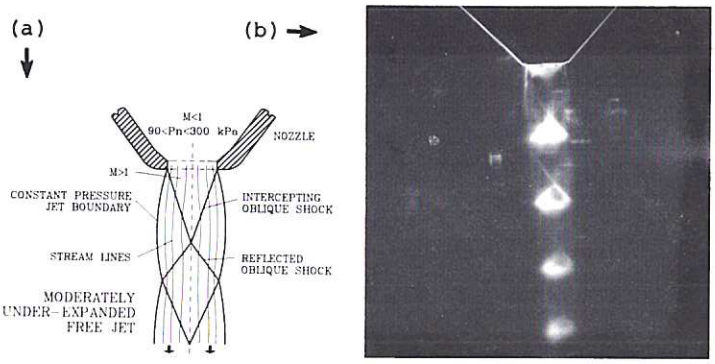


Figure 2. (a). Regular shock intersection at jet axis (b). Schlieren photograph of a jet as in (a).

Figure 2a shows a schlieren photograph of the supersonic jet from a circular nozzle with $P_n/P_a=3$. Formulae can be derived to calculate the wavelength of the periodic shock structure in such a jet [16,17]. The shock structure is essentially caused by the sudden expansion of the gas flow at the edge of the nozzle, resulting in a conical shock which starts at the nozzle edge and which can reflect many times on the jet boundary further downstream (figure 2b). The pressure on the workpiece (the cutting pressure) is associated with the stagnation pressure [1,13] in the gas flow. It can be shown that across a shock the stagnation pressure always decreases. This effect is strongest across a normal shock where the gas velocity always changes from supersonic to subsonic values.

The cutting pressure can be measured with a pressure transducer behind a pinhole in a metal disk simulating the workpiece. The disk probe can be scanned along and transverse to the jet axis (figure 3).

The interaction of the shocks with a workpiece result in a cutting pressure that shows large variations as a function of nozzle stand-off distance (figure 4). It is reasonable to expect that these variations will influence the cutting capability of the gas jet.

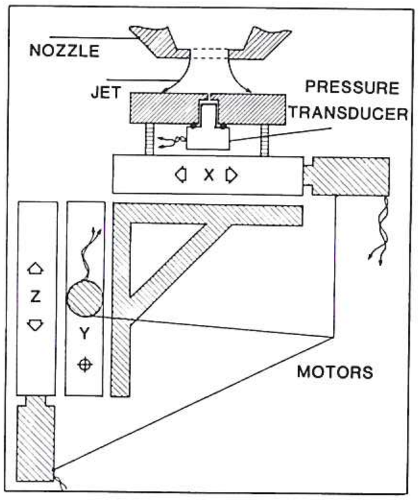


Figure 3. Measuring of cutting pressure.

Several regions of high cutting pressure can be identified. The first high pressure region is referred to as zone A and lies very close to the nozzle tip, making it vulnerable to damage by debris. The next high pressure region (zone B) lies further away from the nozzle tip at a practical, damage resistant position. Other high pressure regions are too far away for use with coaxial focussing optics with practical F-number. Cutting pressures of up to 350 kPa-g at a stand-off distance of 3mm can be reached in zone B with larger tolerances in nozzle stand-off.

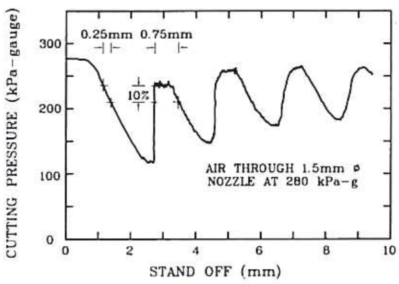


Figure 4. Cutting pressure from a circular nozzle as a function of nozzle stand-off.

Mach shock disk

For higher nozzle pressure ($P_n/P_a>4$) the structure as depicted in figure 2 cannot exist anymore. Instead of regular shock intersection at the jet axis, a strong Mach shock disk (MSD) normal to the gas flow truncates the conical shock, which has become curved (figure 5). The physical phenomena leading to the formation of a MSD are complex and investigated by others [18,19]. The flow downstream of the MSD is subsonic but the flow that has not crossed the MSD can be supersonic (figure 5). The subsonic flow has suffered a large drop in stagnation pressure which would result in a low laser cutting pressure. Figure 6 shows the cutting pressure on a workpiece from a jet with a MSD as a function of nozzle stand-off distance, indicating the lack of periodic structure in the jet and a consistantly low cutting pressure.

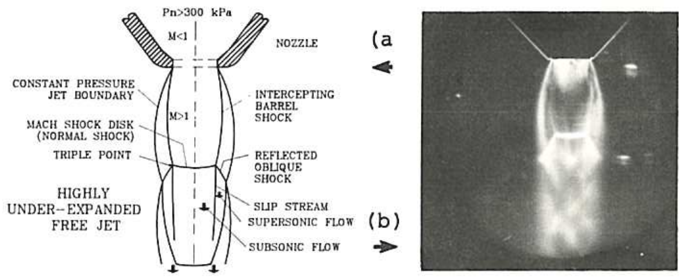


Figure 5. (a). Mach reflection with MSD.
(b). Schlieren photograph of a jet with a MSD

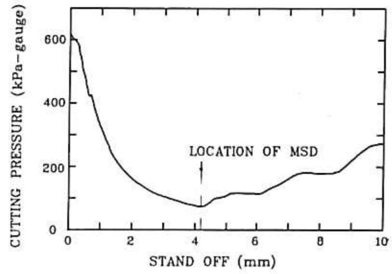


Figure 6. Cutting pressure from a jet with MSD as a function of nozzle stand-off.

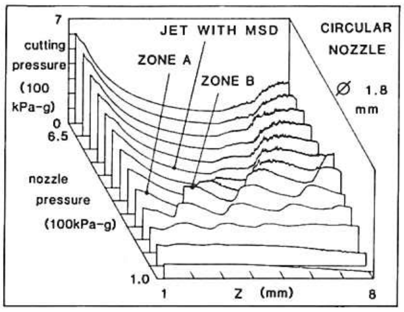


Figure 7. Cutting pressure from a jet from a circular nozzle as a function of nozzle pressure and stand-off.

Figure 7 shows the cutting pressure from a circular nozzle as a function of both stand-off distance and nozzle pressure. There is a transition point at a certain combination of nozzle stand-off and nozzle pressure where the cutting pressure shows a discontinuity as the shock structure changes from zone B to a MSD. The location of this transition point in coordinates of z and P_n is very sensitive to minor damage or irregularities of the nozzle tip[17]. It is understandable that operators of laser cutting equipment who are ignorant of this could experience unexpected irreproduceability of their results.

Stagnation bubble induced by MSD

Other investigators have reported the existence of a vortex ring or stagnation bubble in impinging jets with a MSD [15,20,21,22]. A stagnation bubble or vortex ring is a stable, toroidal body of rotating gas located between the MSD and the surface of the workpiece (figure 8). Minor irregularities at the nozzle tip can break up the vortex ring in separate stagnation bubbles. Visualisation of the streamlines of the gas flow on the workpiece by means of a grease streak method [1,13,15] suggest that a vortex ring could result not only in ineffective debris removal but also to plasma formation due to absorbtion of laser radiation by trapped debris.

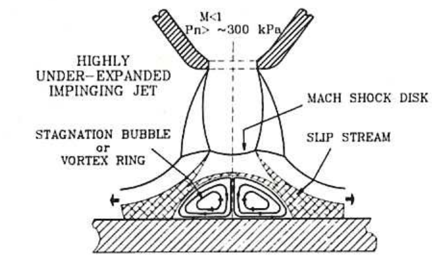


Figure 8. Stagnation bubble or vortex ring.

Non-circular nozzles

It was felt that by breaking the symmetry of a circular nozzle the shock structure in the cutting jet could be changed in such a way that it is impossible for a MSD to appear even at high nozzle pressure. A large number of non-circular nozzle shapes have been investigated by pressure measurement and flow visualisation techniques. This has resulted in the selection of three shapes (figure 9) that give cutting pressures of 500-600kPa-g at a stand-off distance of 4.5-6.5mm (figure 10). Figure 11 shows a schlieren photograph of a jet from a lobed nozzle. Although the lobes of the nozzle exits do not intrude with an F/6 focussed laser beam, it has been found that an F/8 focussed beam gives a safer tolerance to misalignment.

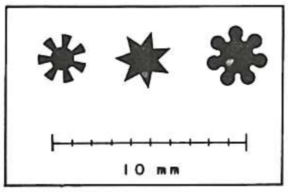


Figure 9. Successful lobed nozzle designs.

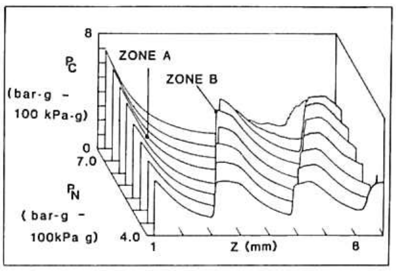


Figure 10. Cutting pressure from star lobed nozzle.

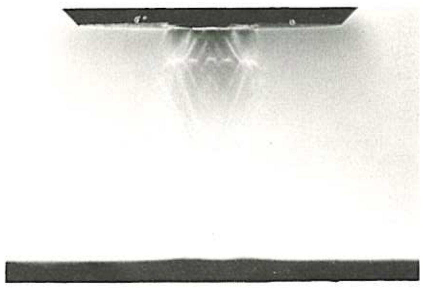
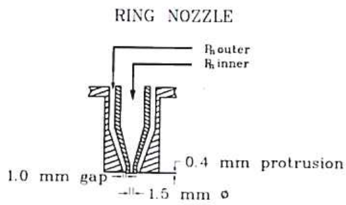


Figure 11. Schlieren photograph of an impinging jet from a lobed nozzle (zone B).



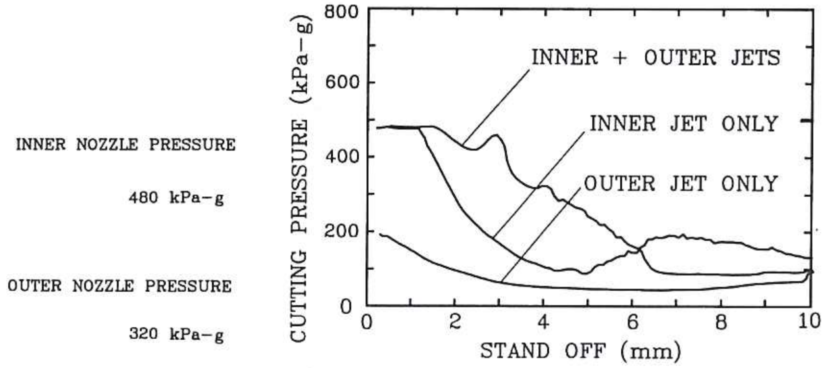


Figure 12. Ring nozzle.

Figure 13. Cutting pressure from ring-nozzle.

<u>Ring nozzle or annular nozzle (after Steen & Gabzydyl [23])</u>

The authors have had the opportunity to examine a ring nozzle (figure 1e) that is being developed at Imperial College of the University of London. Initial observations of this nozzle exposed the ability of the flow through the annular nozzle to influence the local ambient pressure around the central jet. In this way the cutting pressure distribution exerted by the central jet can be modified. The ring nozzle and its cutting pressure characteristics are shown in figures 12 and 13.

<u>Coanda nozzle</u>

The coanda nozzle also consists of a conventional (circular) nozzle surrounded by an annular nozzle (figure 14). The outside of the central nozzle has a rounded contour so that the gas on the streamlines that follow this contour (coanda effect) is given a velocity component directed radially towards the centre of the inner jet. Because of this, the central jet experiences a local ambient pressure P_a which is higher than atmospheric, resulting in a lower ratio P_{ni}/P_a (P_{ni} is the nozzle pressure in the central nozzle). This has as a consequence that for a nozzle pressure of the central jet at which a MSD would exist, there is still regular intersection of the shock from the nozzle edge (figure 3). Figure 15 shows a schlieren photograph of an impinging jet from an early design coanda nozzle and figure 16 shows the cutting pressure from a coanda nozzle with a more curved inner nozzle contour.

Current coanda nozzles are capable of exerting a cutting pressure of 500 kPa-g at a stand-off distance of 4-5mm, the nozzle pressure in the inner nozzle being 700 kPa-g and in the outer 350 kPa. This makes it possible to use coanda nozzles with focussing optics to F/4.

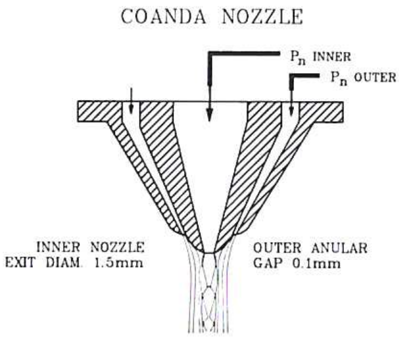


Figure 14. Coanda nozzle.

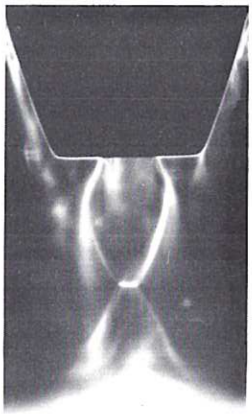


Figure 15. Schlieren photograph of an impinging jet from a coanda nozzle.

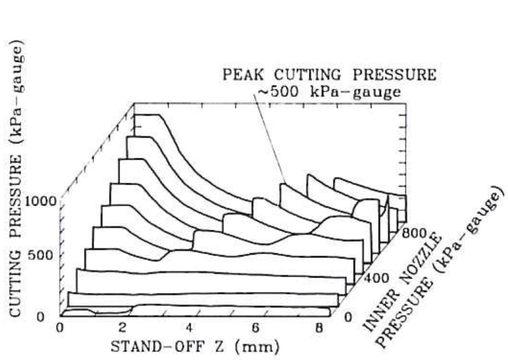


Figure 16. Cutting pressure from a coanda nozzle.

Tri-jet for mirror focussing (after Sepold & Rothe [8])

Very high power CO_2 laser beams (> 3kW) cannot be focused with a lens because the power density imposes too high a thermal distortion in the lens. Laser cutting with mirror focusing can be performed with one or more off-axis nozzles. Symmetry with regard to cutting direction requires a number of concentric off-axis nozzles.

The mirror focussing nozzle described here consists of three circular conical nozzles each at an angle of 60° with the horizontal (figure 17), designed for a stand-off distance of 3-4mm.

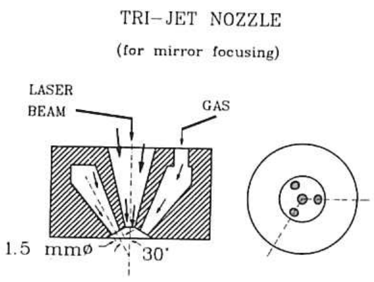


Figure 17. Tri-jet.

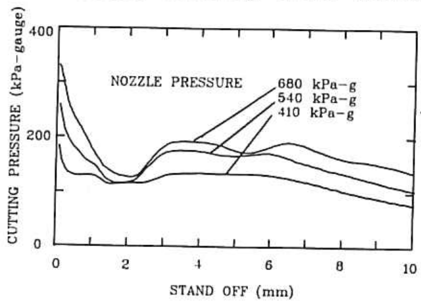


Figure 18. Cutting pressure from tri-jet.

Figure 18 shows the cutting pressure along the nozzle axis as a function of nozzle stand-off. The intersecting jets are seen to exhibit a behaviour which differs from that displayed by a single jet. There is an extended zone B but cutting pressures are limited to 200 kPa-g.

Flat-tipped nozzle

The lobed nozzles used in this investigation have flat tip of about 10mm diameter. Cutting pressure scans at small nozzle stand-off (typically 0.25mm) reveals some remarkable features which applies to flat tipped nozzles in general (figure 19). The central area of the flow shows a positive cutting pressure but as the flow moves radially outwards this pressure drops to values below atmospheric pressure. The total pressure exerted by the jet on the workpiece can be obtained by numerically integrating the cutting pressure over the whole of the flow field. The nett force can be negative. This can be interpreted as suction towards the nozzle. These phenomena are inherent for radially expanding supersonic flows [24] and are exploited in other industrial applications [25].

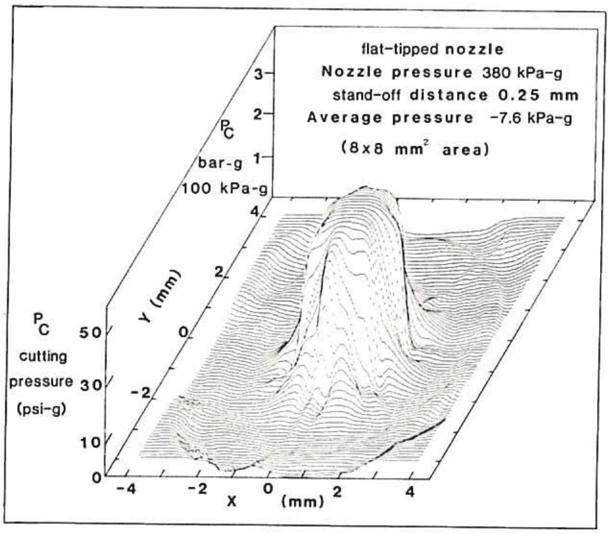


Figure 19. Cutting pressure profile of a flat-topped nozzle at small stand-off distance.

It is suggested here that flat tipped nozzles operated at supersonic pressures (P_n>140 kPa-g) can show adverse cutting properties if the nozzle stand-off is small [5,7,9]. It is possible that molten material from the cut which is still present after the positive pressure region of the nozzle has passed over it can be drawn back into the cut kerf.

Cutting performance of supersonic jets

Cutting trials and tool setting techniques with circular and lobed nozzles have been described elsewhere [1]. Figure 20 shows an example of the cutting results with a 1.5mm diameter circular nozzle at a stand-off of 3.5mm. Figure 21 shows results with a lobed nozzle at a nozzle stand-off of 6.5mm.

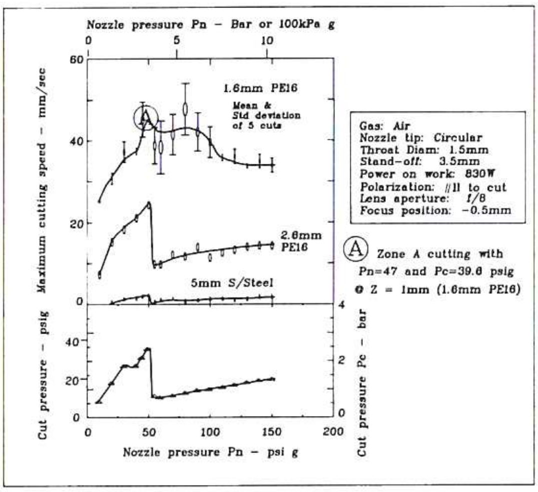


Figure 20. Cutting trials with a 1.5mm diameter circular nozzle (plane of polarization parallel to cut).

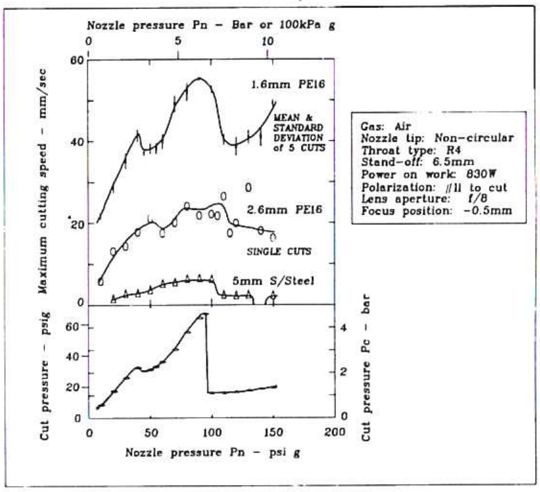


Figure 21. Cutting trials with a lobed nozzle (plane of polarization parallel to cut).

Conclusions and discussion

Although it was not practical to guarantee a repeatable laser working point with on-line laser beam diagnostics, a number of important conclusions can be drawn from the experiments described here:

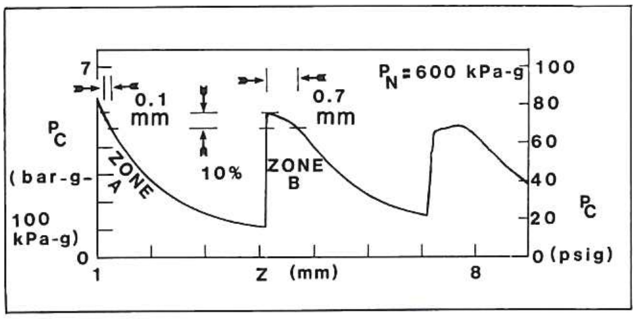


Figure 22. Lobed nozzle stand-off tolerance.

* maximum cutting speed is positively correlated to cutting pressure from circular and lobed nozzles;
* with supersonic jets, there is a strongly non-linear relation between nozzle stand-off and cutting pressure;
* it is recommended to monitor cutting pressure as well as nozzle pressure as input variables of the cutting process;
* with a circular nozzle, it is possible to reach the same cutting pressure at large nozzle stand-off (zone B) as with conventional small stand-off (zone A), but with larger tolerances in nozzle stand-off (figure 4);
* non-circular nozzles and coanda nozzles are capable of much higher cutting pressures (500-600 kPa-g) at larger nozzle stand-off (4-6.5mm) than circular nozzles and show a larger tolerance in zone B than in zone A (figure 22);
* maximum cutting speed in zone B with circular and lobed nozzles is the same as in zone A (figures 20 and 21);
* many of the cuts with a lobed nozzle in zone B were nearly dross-free;
* no nozzle damage was observed from cuts in zone B with a lobed nozzle;
* the occurrence of a Mach shock disk with the possible formation of a vortex ring can be associated with poor cutting performance;
* working in zone B of a lobed nozzle results in an improvement of repeatability;
* a coanda nozzle gives a cutting pressure profile very similar to that of a lobed nozzle but at a slightly smaller stand-off distance (4-4mm).

A lobed nozzle offers advantages over a circular nozzle in a number of cutting applications. However, the delicate lobed structure of the tip requires accurate alignment of the laser beam with an F-number not less than 8. This is not a practical disadvantage since the required alignment accuracy is not more stringent than the process tolerance needed between the focus of the beam and a jet from a conventional nozzle. The high pressure inside a lobed nozzle (>600 kPa-g) requires a focussing lens of sufficient thickness.

A coanda nozzle has a zone B that lies closer to the nozzle than that of a lobed nozzle. This makes it possible to use optics with an aperture as wide as F/4, this being the F-number that gives the smallest possible spot size (for 10.6 μm radiation from a CO_2 laser) with conventional singlet lenses. Two separately adjustable supplies of compressed gas may be required to operate this nozzle.

An array of off-axis nozzles (tri-jet) can be used in mirror focussing applications. The cutting pressure is, however, limited to 200 kPa-g.

It is possible that a number of reported [3,5-7,9] disappointing cutting performances with high pressure nozzles are caused by inadvertent selection of the wrong nozzle stand-off distance (i.e. in between zone A and zone B) or by the use of a flat tipped nozzle where suction effects may occur.

References

1. Fieret, J., Terry, M.J., Ward, B.A., "Aerodynamic interactions during laser cutting", Proc. SPIE 1986 Int. Symp. on Optical and Opto-electronic Applied Sciences and Engineering, Conference on Laser processing: Fundamentals, Applications and Systems Engineering, Quebec, Canada, 2-6 June 1986.

2. Kimura, S., Kinoshita, J., Nakamura, E., Ishikawa, K., "Thick mild steel cutting with high power CO_2 laser", Proc. 2nd Int. Metal Cutting Conf., Wuhan, May 1985.

3. Arata, Y., Maruo, H., Miyamoto, I., Takeuchi, S., "Quality in laser-gas-cutting stainless steel and its improvement", Trans. JWRI 10 (1981), 2, 129-139.

4. Steen, W.M., Kamulu, J.N., "Laser cutting", in "Laser materials processing", ed. Bass, M., North-Holland Publishing Co. (1983).

5. Nielsen, S.E., "Laser cutting with high pressure cutting gases and mixed cutting gases", PhD thesis, Inst. Manfg. Eng., Tech. Univ. of Denmark (1985).

6. Forbes, N., "The role of the gas nozzle in metal cutting with CO_2 lasers", Proc. Opto-electronics Conf./Laser 75, Am. Soc. for Metals 1983.

7. Olsen, F.O., "Investigations in optimizing the laser cutting process", Proc. ASM Conf. on Lasers in Materials Processing, Munich 1975.

8. Sepold, G., Rothe, R., "Laser beam cutting of thick steel", Proc. Material Processing Symp., ICALEO'83, Los Angeles, CA, USA, LIA vol. 38.

9. Thomassen, F.B., Olsen, F.O., "Experimental studies in nozzle design for laser cutting", Proc. "Lasers in Manufacturing 1" Conf., Brighton, UK, 1983.

10. Vicanec, M., Simon, G., Urbassec, H.M., Decker, I., "Hydrodynamical instability of melt flow in laser cutting", J. Phys. D: Appl. Phys. 20 (1987), 140-145.

11. Schuocker. D. Abel, W., "Material removal mechanism of laser cutting", Proc. SPIE Linz, Austria 26-28 Sept., 455 (1983), 88-95.

12. Settles, G.S., "A direction indicating colour schlieren system", AIAA J. 8 (1970), 12, 2282-84.

13. Fieret, J., Ward, B.A., "Circular and non-circular nozzle exits for supersonic gas jet assist in CO_2 laser cutting", Proc. "Lasers in Manufacturing 3" Conference, Paris, France, 3-5 June 1986.

14. Courant, R., Friedrichs, K.O., "Supersonic flow and shock waves", Interscience Publishers Inc., New York.

15. Donaldson, C. Dup., Snedeker, R.S., "A study of free jet impingement. Part 1. Mean properties of free and impinging jets", J. Fluid Mech. 45 (1971), 2, 281-319.

16. Prandtl, L., "The essentials of fluid dynamics", Blackie & Son, Glasgow (1952).

17. Ward, B.A., "Supersonic characteristics of nozzles used with lasers for cutting", Proc. SPIE Int. Congress on the Application of Lasers and Electro-optics, Boston, MA, USA, 12-15, Nov. 1984.

18. Abbett, M., "The Mach disk in underexpanded exhaust plumes", AIAA 8th Aerospace Sciences Meeting, New York, Jan. 19-21 1970. AIAA paper no. 70-231.

19. Chang, I.S., Chow, W.L., "Mach disk from underexpanded axisymmetric nozzle flow", AIAA J. 12 (1974), 8, 1079-82.

20. Ginzburg, I.P., Semiletenko, B.G., Uskov, V.N., "Experimental study of underexpanded jets impinging normally on a plane baffle", Fluid Mech. Sov. Research 4 (1975), 3, 93-105.

21. Kalghatgi, G.T., Hunt, B.K., "The occurrence of stagnation bubbles in supersonic jet impingement flows", Aeronautical Quarterly (Aug. 1976), 169-185.

22. Gubanova, O.I., Lunev, V.V., Plastinina, L.N., "The central breakaway zone with interaction between a supersonic underexpanded jet and a barier", Fluid Dyn. 6 (March 1973) 298-301.

23. Steen, W.M., Gabzydyl, J, private communication 1987.

24. Von Mises, R., "Mathematical theory of compressible fluid flow", Academic Press, New York (1958), pp. 73-77.

25. Phibbs, L.W., "On transitions in radial flow between closely-spaced parallel plates", J. Phys. D: Appl. Phys. 14 (1981), L197-L201.