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SUPERSONIC CHARACTERISTICS OF NOZZLES USED WITH LASERS FOR CUTTING

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Abstract

Many operators of laser cutting equipment use supersonic flow of a cut-assisting gas from a nozzle directed at the workpiece. This flow gives rise to shock-fronts which can cause large,localised variations in the effective gas pressure on the workpiece. This work has used pressure measurement techniques to investigate the variations in air-jet pressures. It is possible to identify the optimum value of parameters that will result in a high pressure on the workpiece. CO_2 laser cutting trials demonstrate the strong correlation between the workpiece pressure and maximum cutting speed. The pressure measurements reveal the sensitivity of the flow pattern to nozzle damage and manufacturing variations. A simple nozzle 'tool-setting' and damage inspection technique is proposed. This technique is compatible with an industrial production environment.

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Introduction

Gas assisted material cutting with a CO_2 laser involves the focusing of a high power beam onto the surface of the workpiece and simultaneous removal of the molten or decomposed products by a jet of compressed gas. This gas can be inert to protect the workpiece from oxidation or contamination. Alternatively, an active gas may be used to assist the process with an exothermic reaction. The jet is formed by using either a co-axial nozzle, concentric with the axis of the focusing optics, or an off-axis nozzle directing its jet at the interaction point.

Conventional use of laser cutting systems has been demonstrated to provide an economical and reliable production process. However, there are a number of examples of more demanding applications where cut quality, penetration or cutting speed has been found to be unpredictable or lacking in reproducibility. Some systems, in the hands of experienced and careful operators, have given many years of reliable service. Other systems, having nominally identical designs, have been reported to yield variable results.

The observations of nozzle characteristics described in this paper result from a programme of work aimed at identification of the critical input parameters of the cutting process together with estimation of their optimal values and tolerance of the process quality to their variation.

The efficiency and reproducibility of removal of molten metal from a cut kerf can be shown to be strongly correlated with the pressure exerted by the cutting gas on the workpiece surface. Many laser cutting systems operate with nozzle pressures above 18 psig where the flow becomes noticeably supersonic. Above this pressure the flow pattern is a complex function of the pressure applied to the nozzle, the diameter and shape of the throat and tip of the nozzle and the distance between the tip and the workpiece.

Measurement of the pressure distribution in a supersonic jet, as a function of the nozzle and gas parameters, has been performed on nozzle designs in common use. These observations clearly identify the operating range of input parameters that will lead to a high, material removing gas pressure on a workpiece surface. It is also possible to identify areas of design or operation of a nozzle which can result in a disproportionately low pressure on the workpiece. Measurement of the pressure distribution also reveals abnormal flow patterns that result from manufacturing imperfections or operational damage in a nozzle tip. This observation suggests a procedure that is suitable for remote inspection of a nozzle prior to production operations.

Gas flow from nozzles

It is possible to photograph one of the dominant effects in a supersonic jet (figure 1). Creation of the stationary pressure waves in the flow pattern of these jets has been studied by Prandtl (1).

Figure 1. Schlieren photograph of the stationary pressure wave in a supersonic jet

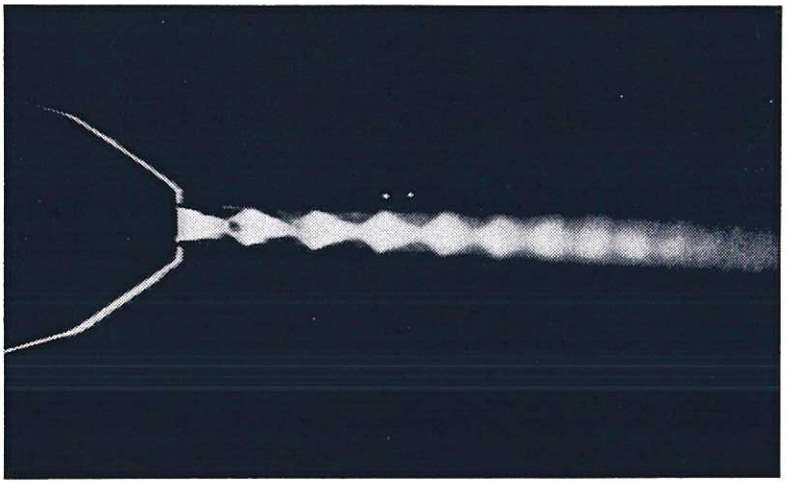
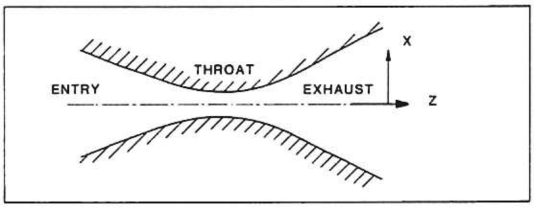


Figure 2.
Generalised deLaval nozzle



A simplified view of a cutting gas nozzle consists of a reservoir maintained at a constant stagnation pressure P_n and exhausting through a 'conical' nozzle with throat diameter D_n. The generalised case is a nozzle with a converging entry section leading to the throat and followed by a diverging exhaust section, the deLaval nozzle. The ambient gas pressure outside the nozzle is P_a and the geometry is that shown in figure 2.

There are two dominant forms of flow of the gas escaping from the high pressure reservoir through a deLaval nozzle. The first form of flow consists of expansion of the gas (ie reduction of density and increased flow velocity) in the entry section of the nozzle followed by compression in the exhaust section. The flow velocity of the gas remains subsonic throughout. This condition prevails as long as the ratio of the reservoir pressure to ambient pressure remains below a critical value. The second form of flow occurs above this critical pressure ratio where the flow becomes supersonic at the throat and continues to expand thereafter (2).

The description of supersonic flow is complex and dependent on the precise details of the shape of the exhaust section and the pressure ratio. In general, the jet becomes detached from the nozzle wall after interaction with a shock front. The flow then continues as an entity that is separated from quiet ambient gas by a discontinuity surface which is a vortex layer. This layer becomes thicker along the jet and ultimately consumes it.

An approximate description of the nozzle flow can be obtained by assuming adiabatic, irrotational flow of a perfect gas (2). This analysis predicts that the transition from subsonic to supersonic flow will occur when the pressure ratio is:-

$$\frac{P_n}{P_a} = (1+1/n)^{1+n/2} \qquad \{1\}$$

This ratio is listed for gases of interest in laser cutting in Table 1.

Table 1 - Pressure ratio above which supersonic flow occurs. P_n is the nozzle pressure, P_a is the ambient pressure and n is the number of degrees of freedom of the gas molecules

Gas		n	P_n/P_a
Monatomic	eg He, Ar	3	2.05
Diatomic	eg Air, O_2, H_2	5	1.89
Polyatomic	eg CO_2	>5	<1.85

The description of supersonic flow phenomena after jet detachment from the nozzle wall again is complex and dominated by the pressure ratio. The shock front that leads to jet detachment penetrates the flow as a conical converging front. In the area where the shock fronts and their associated waves interact, the shock cone is truncated by a Mach Shock Disc (MSD) as shown in figure 3. After this interaction a diverging, conical shock front emerges until it is reflected from the vortex layer to repeat the above cycle. The gas flowing in the jet crosses the shock fronts and suffers changes in its direction, velocity and pressure. The zones inside the shock cones exhibit a pressure that can be considerably higher than that outside the cones.

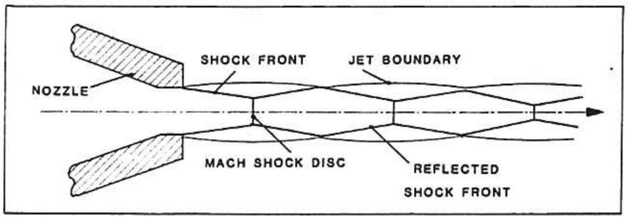


Figure 3. Prandtl waves

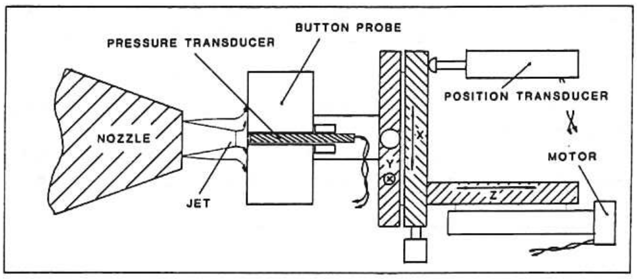


Figure 4. Pressure scanning apparatus

The apparent wave nature of supersonic jet flow has been studied by Prandtl (1). His empirical formula for the wavelength of the phenomena in real gases is:-

$$L = 0.89\ D_n\left(P_n/P_a - 1.9\right)^{1/2} \qquad \{2\}$$

This formula suggests that this form of supersonic flow occurs only at pressure ratios greater than 1.9, a value similar to the critical values given in Table 1.

Experimental methods

Pressure measurement techniques have been used to investigate the performance of conical cutting nozzles (qv figure 5). The pressure measurement is intrusive and modifies the flow pattern. However, the probe geometry has been chosen to give measurements that are representative of the pressure experienced by the molten surface of a potential laser cut. Optical flow visualization techniques have been used but, in general, give only qualitative results.

A 1.6 mm diameter, piezo-resistive pressure transducer is used to measure the pressure on a simulated workpiece surface. The transducer is mounted in the centre of a 40 mm diameter button behind a 0.2 mm diameter pinhole, the latter being flush with the surface of the button. The amplified output of the transducer is connected to the Y-axis of an X-Y recorder. Calibration is performed by sealing the probe to the tip of the nozzle, the pressure in which is monitored by a precision dial gauge. A further pressure transducer is used to record the nozzle pressure during automatic plotting.

The pressure displayed by the jet measuring transducer is a combination of the dynamic and static pressure in the flow attenuated by passage across the shockwave in front of the probe. Since these tests are designed to indicate the force that might be experienced by the molten metal in a laser cut, no 'supersonic pitot' correction has been applied.

The pressure distribution around a nozzle tip is explored by mounting the probe on an x-y-z translating table, the axes of which are equipped with drive motors and position transducers (figure 4). The output of the various transducers can be fed to the Y-axis of the recorder to produce graphical records of the pressure distributions.

The conical nozzle that has been examined in considerable detail is shown in figure 5. The nozzle throat is a drilled, parallel sided hole in a copper tip that has been brazed onto the end of a matching brass cone. The tip is mechanically de-burred, a process which can result in a non-reproducible shape of the exhaust section of the nozzle.

Schleiren photograpy of the flow pattern occasionally reveals a nozzle where the jet emerges at an angle to the cone axis. Deviations up to 10° have been detected. This indicates that the flow characteristics can be very sensitive to manufacturing imperfections and damage from careless handling or from cut debris.

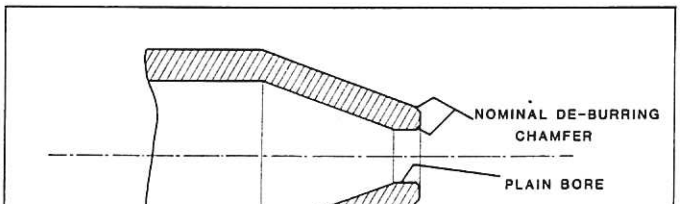


Figure 5 A laser cutting nozzle

Nozzle investigation

Variations in the effective pressure on a workpiece at the centre of the jet axis are shown in figure 6. Sharp variations in workpiece pressure are evident as is the sensitivity of this pressure to small variations in distance at the conventional working range of 1 to 2 mm.

This graph was obtained from an automatic scan of the supersonic jet with the probe positioned to move along the axis of the jet. Subsequent scans with the probe moved to increasing radii of the jet enabled the plotting of an isometric representation of the two-dimensional pressure distribution. This is shown in figure 7.

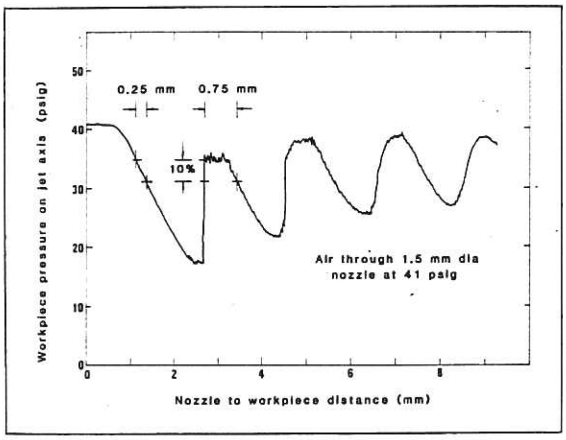


Figure 6. Variation of pressure on workpiece with nozzle distance.

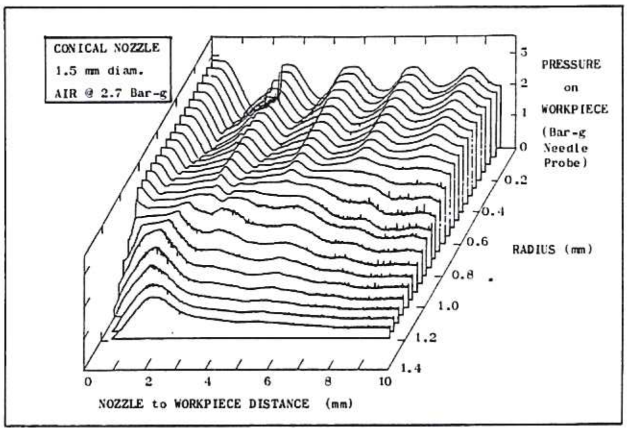


Figure 7. Radial profile of workpiece pressure distribution

There are flow features in the radial pressure profile shown in figure 7 which can be identified with the features depicted in figure 3. This identification is made in figure 8.

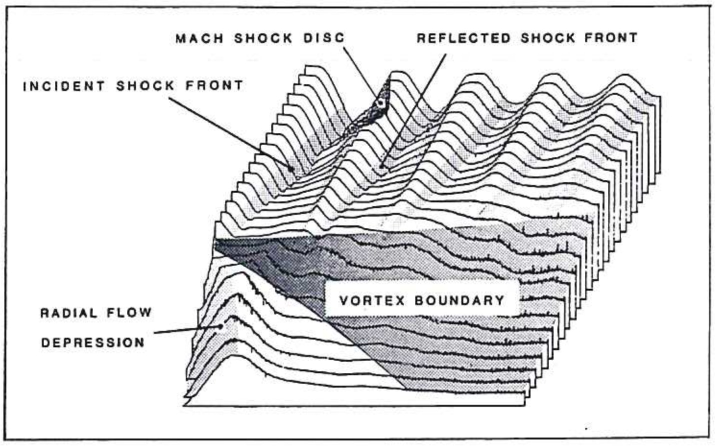


Figure 8. Detectable features in the radial profile of the workpiece pressure pattern

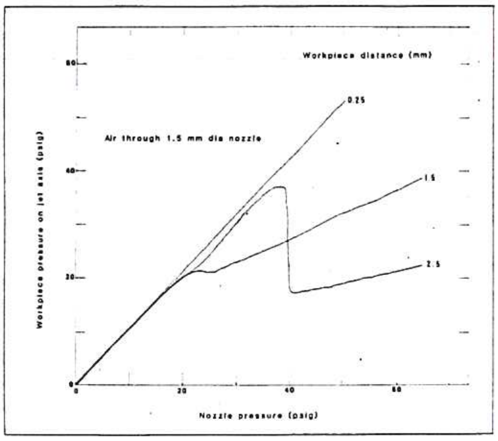


Figure 9. Dependence of workpiece pressure on nozzle pressure

Another method of scanning the performance characteristics of a cutting nozzle consists of recording the workpiece pressure as a function of nozzle pressure. An example of this scan is shown in figure 9. This shows that there is a range of working distances from the nozzle where there is a precipitous, and perhaps unexpected, drop in workpiece pressure resulting from a small increase in nozzle pressure. This drop is accompanied by a noticeable change in the acoustic emission of the interaction of the jet with the workpiece. Furthermore, adjustment of the nozzle pressure to coincide with this discontinuity results in a widely fluctuating and unstable condition with a considerable variation in noise output.

It is possible to compare nozzle performance with the predictions of Prandtl wavelength given in equation {2}. This can be displayed graphically by performing repetitive axial scans, of the type shown in figue 6, while incrementing the nozzle pressure (and position of the plotter pen) between scans. An example of this procedure is given in figure 10. This gives a clear picture of the 'landscape' which is being investigated for optimum location of a laser cutting working point.

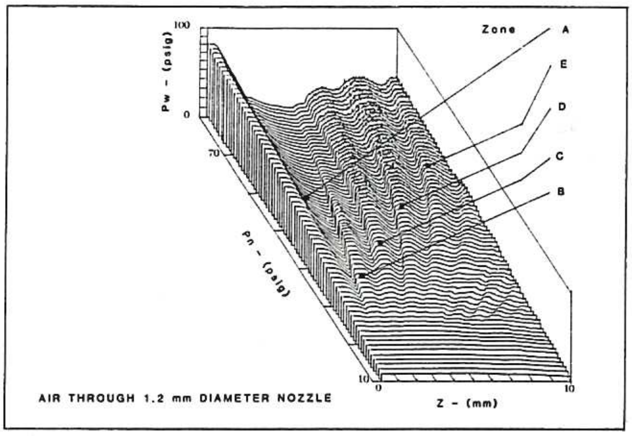


Figure 10. Pressure on workpiece on jet axis (Pw) vs nozzle pressure (Pn) vs workpiece distance (Z)

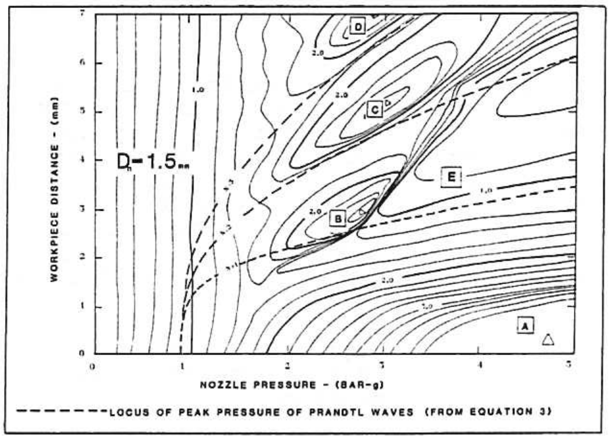


Figure 11. Contours of workpiece pressure on nozzle axis as a function of nozzle pressure and working distance

A more useful presentation for the selection of a laser cutting working point is a contour diagram of the landscape. This is given in figure 11 for air through a 1.5 mm diameter nozzle. The most noticable characteristic of these diagrams is the fact that there are a number of discrete, isolated zones (labeled A to D) where significant pressures can be applied to the molten metal of a potential cut. Zone A occurs when the nozzle is close to the workpiece (<1.5 mm). In this area the gradients of workpiece pressure against distance and nozzle pressure are monotonic and steep. This implies that cutting performance has very little tolerance to variation of these parameters. A 10% drop in cutting pressure (pressure on workpiece) results from ~0.25 mm increase in nozzle distance or ~1.5 psi decrease in nozzle pressure.

Zone B is the area that is relevant to most cutting applications. It occurs at a reasonable, damage resistant distance from the nozzle where there is little turbulence or fine-scale variation in cutting pressure and where the gradients of the surface pass through a zero (ie. the working point is on a plateau). The tolerance to distance variations is ~0.7 mm and pressure variations of ~5 psi are permissible. However, it should be noted that increase of nozzle pressures outside this tolerance would result in a precipitous drop in cutting pressure.

Zones C and D occur at greater distances from the nozzle. They are characterised by turbulence and fine-scale variations in cutting pressure. Furthermore, these zones occur at such a distance that the smaller diameter nozzles would intrude into an f/6 cone and so are unsuitable for use as co-axial nozzles. The higher nozzle pressures in these zones require a larger mass flow-rate and a consequent increase in process costs.

The distances between zones B,C & D etc are predicted by the Prandtl formula {2}. Inspection of the position of the zones relative to the nozzle tip suggest a simple modification of equation {2} which yields an adequate prediction of the locus of the peak cutting pressure as a function of nozzle pressure and working distance.

$$L_w = D_n\,[0.5 + 0.89\,N\,(P_n/P_a - 1.9)^{1/2}] \qquad \{3\}$$

Where Lw is the distance between nozzle tip and the workpiece, Dn is the diameter of the throat of the nozzle and N is the Prandtl 'wave-number'. This function is evaluated and superimposed on the experimentally derived contour diagram in figure 11.

Equation {3} gives no information on the magnitude of the peak pressure. The contour diagram shows that the high pressure ridges at B & C decay at higher nozzle pressures.

Examination of a series of isometric displays (eg figure 7) shows that the diameter of the MSD reduces with increasing pressure and the incident conical shock-fronts appear to interact and eventually consume the following pressure peak on the axis. This effect results in abnormally low pressures in areas where equation {3} might predict the peak of a Prandtl wave (eg Zone E).

Zone B has been examined in detail by determining the nozzle pressure and working distance that results in the maximum cutting pressure in this zone. These optimum values, which have been determined for a number of nozzles with different diameters, are recorded in figure 12. Although the greatest pressure appears to be produced by the smallest diameter nozzle, it should be noted that the position of Zone B places the throat of these nozzles very close to an f/6 laser focus cone.

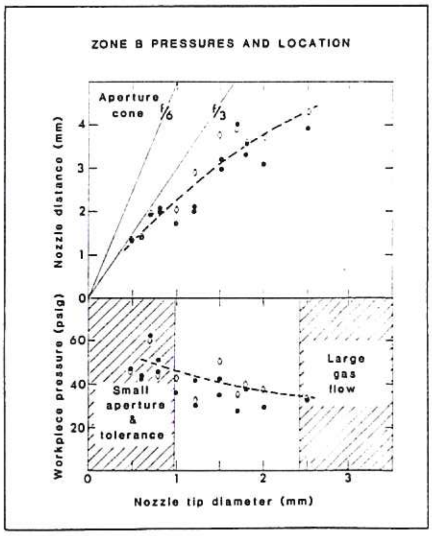


Figure 12. Location of Zone B and maximum cutting pressures as a function of nozzle diameter.

Laser cutting trials

The assumption that has been made in using the phrase 'cutting pressure' to replace 'pressure on the workpiece' has been tested by measuring the maximum attainable cutting speed as a function of nozzle pressure at a nozzle distance that extends to Zone B. The results of repetitive trials at a number of pressures and the pressure measured on the workpiece surface are recorded in figure 13. These trials were performed by subjecting the moving workpiece to a uniform acceleration after an initial penetration pause and traverse over a short distance at a constant velocity. Measurement of the length of fully penetrating cut permitted an accurate estimation of the maximum cutting speed. Care was taken to ensure that all other identified input parameters of the cutting process were maintained within close limits during the trials. The laser beam was circularly polarized; nozzle height was maintained within 0.07 mm of the chosen height; the laser focus was positioned concentric with the jet axis within a previously determined limit, while other parameters were monitored at intervals during the trials.

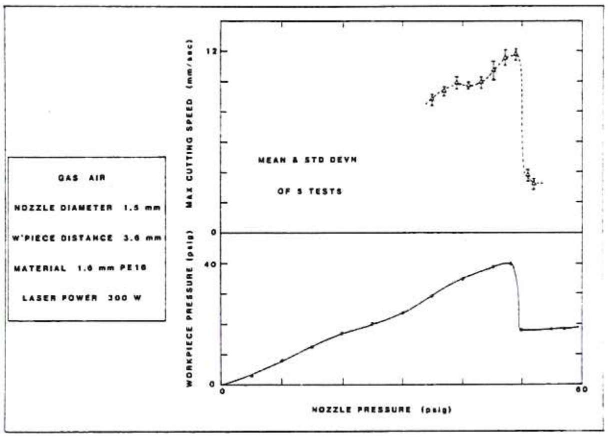


Figure 13. Maximum cutting speed and cutting pressure (on jet axis) as a function of nozzle pressure

The correlation between the pressure on the workpiece and the maximum cutting speed is statistically significant.

Nozzle damage and inspection

The reasons for the scattered distribution, of the optimum parameters in Zone B recorded in figure 12, has been examined by performing transverse pressure profile scans of a selection of nozzles. These profiles are obtained by performing a diametral X-scan across the jet at discrete distances (Z) from the nozzle tip. An example of the profile of the jet from an accurate, undamaged nozzle tip is given in figure 14. Included in this figure are transverse X-Y profiles obtained by performing a sequence of chordal X-scans across the jet (indexed Y). These transverse profiles were taken in the area of the jet just in front of the Mach Shock Disc and again, behind the MSD in Zone B. A comparison of these transverse profiles shows a significant difference in the form of the cutting pressure distribution in these areas. In Zone B the profile is smooth and reproducible whereas, in front of the MSD, although the transverse profile is 'flat-topped', it exhibits considerable turbulence and fine-scale variation around the edge.

It has been observed that the shape of transverse profiles in front of the MSD are extremely sensitive to damage or imperfections in the rim of the nozzle tip (figure 15).

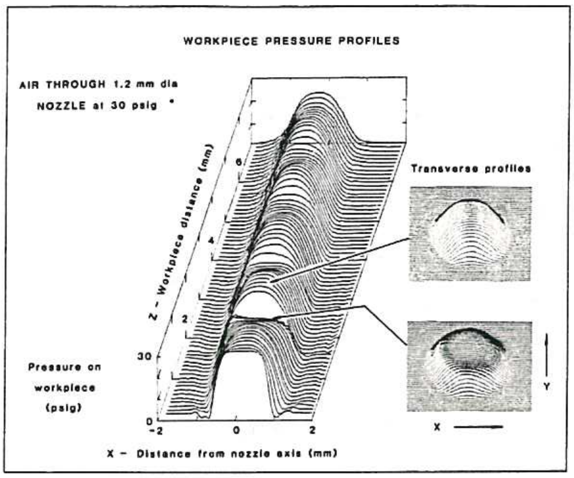


Figure 14. P-X-Z cutting pressure profile with sample X-Y transverse profiles.

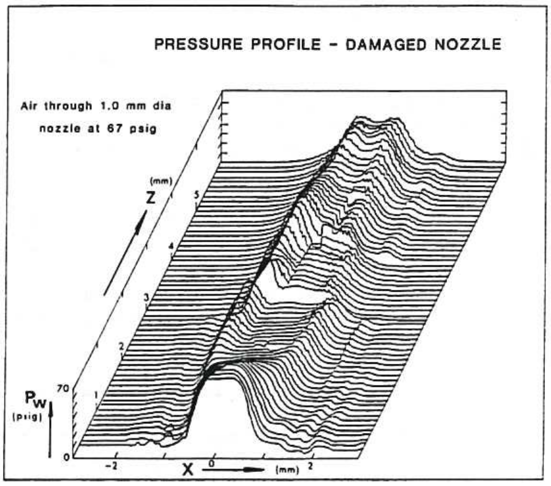


Figure 15. P-X-Z profile of the jet from a damaged nozzle.

The above observations of pressure profiles suggest a simple procedure for use in setting a nozzle at its optimum cutting height and inspecting the tip for manufacturing or damage induced imperfections. The equipment required simply consists of a plate in which is drilled ~0.5 mm diameter hole and which is joined by a union and flexible pipe to a precision pressure gauge. The plate is mounted on a small X-Y table to permit manual transverse movement under the nozzle. The plate is placed in the position of the workpiece at a distance from the nozzle tip which is obtained by interpolation from figure 12. A nominal 'subsonic' gas pressure is applied to the nozzle and the plate is traversed in X and Y to maximise the observed cutting pressure and centre the jet axis on the hole in the plate. With the correct selection of nozzle distance, slow increase of the nozzle gas pressure will permit location of the MSD by observing the nozzle pressure which results in the precipitous drop in cutting pressure. Reduction of nozzle pressure by 2 to 5 psi below this point will place the working point comfortably inside Zone B. The observed cutting pressure is the cutting input parameter that should be maintained between cutting tasks and nozzle changes to assist in process reproducibility. The Zone B cutting pressure can be modified by suitable changes in working distance and nozzle pressure. It is quite possible that different nozzle distances and pressures will be required to maintain the same cutting pressure from nominally identical nozzles.

The same equipment used for setting the nozzle parameters to operate within Zone B can be used to inspect for nozzle damage. Initially the nozzle pressure is set at the working point so that the probe hole is behind the MSD. Reduction of the nozzle pressure by a few psi causes the MSD to move to a virtual position behind the test plate. Manual transverse scan of the hole across the jet, sequentially in the X and Y directions, will permit observation of the symmetry of the cutting pressure in the 'pre-MSD' region. Graphically recorded examples of these scans are shown in figure 16. The asymmetry in cutting pressure at the rim of the transversed profiles is easily detectable and experience soon enables an operator to distinguish between 'good' and 'poor' nozzles.

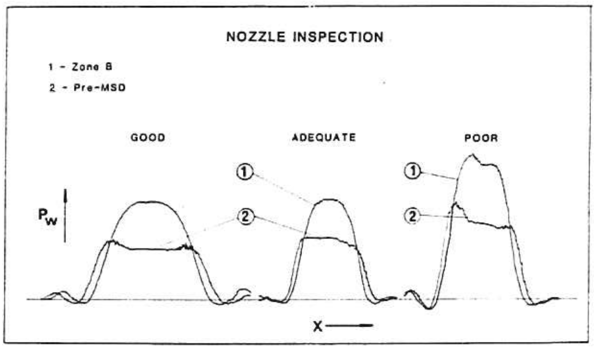


Figure 16. Transverse pressure profiles around the MSD from a variety of nozzles.

The suggested setting and inspection procedure can be incorporated in automatic NC processing operations. A permanent nozzle inspection area can be installed at a standard height in, say, a corner of an X-Y cutting table to which the cutting head could be returned at appropriate intervals. Automatic transverse scans of the fixed cutting pressure measurement hole could be assessed, by a pressure transducer and appropriate software, for the suitability for duty of the current nozzle.

Conclusions and recommendations

The conclusions to be drawn from pressure measurements of the gas flow from laser cutting nozzles and associated cutting trials suggest that the most reproducible cutting performance will be obtained either by working with subsonic flow (ie. at nozzle pressures less than 18 psig) or by:-

(a) working in Zone B (ie. with the workpiece placed just past the first Mach Shock Disc),

(b) use of a pressure probe (eg. precision dial gauge and workpiece simulating pressure probe) to locate the shock disc,

(c) use of cutting pressure and not nozzle pressure as the measured process input parameter,

(d) measuring cutting pressure and inspection of jet asymmetry prior to processing,

(e) imposing tight quality control on the nozzle tip finish,

(f) designing the nozzle and its operating environment to present maximum resistance to debris damage,

(g) taking care to protect nozzles from handling damage or misuse

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