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ABSTRACT

Within the power range 0.01~22kW, commercially-available CO_2 industrial lasers now ncorporate microwave, RF, AC and/or DC electrical excitation technologies, with a orrespondingly wide variety of gas flow and optical extraction geometries. This paper ummarizes from an applications viewpoint some of the advantages claimed for the various pproaches, making brief comparisons with Nd:YAG performance. Particular emphasis is given o the importance of laser brightness, reproducibility, and fluctuation-stability for uses uch as the heat-treatment, cutting, or welding of steels in the thickness range 10-25mm.

1. INTRODUCTION

The variety of CO_2 laser designs commercially available for industrial laser applications s now considerable. Within the relatively modest average power (P) range of 0.01~25kW the rimary excitation is always electrical, but may involve either microwave, RF, AC or DC ischarges parallel or transverse to any gas flow - and with a wide choice of optical esonator and beam-extraction geometries. This paper first summarizes some of the gas flow nd excitation technologies described in the literature for the higher end of this power ange. From the point of view of the user each of the various approaches will usually have ome obvious advantages and disadvantages - e.g. lower helium consumption might have to be alanced against higher initial capital cost; and better mode quality against greater actory floor-space ("footprint"), running cost, or more frequent servicing. The ability to ulse-modulate and numerically control the output may also be important considerations for rofile cutting etc. Less obviously the brightness, reproducibility and fluctuation-tability of the laser are often important technical issues which should also be included in ny economic assessment of the 'best' laser for a particular application. Such factors, and ome illustrative multikilowatt applications, are discussed in subsequent sections of the aper.

2. MULTIKILOWATT INDUSTRIAL LASERS

Published parameters and performance of some industrially-rated multikilowatt CO_2 lasers re summarized in Table 1. With the exception indicated, systems operating at cw power evels ≥10kW have so far been developed around a transverse (sub-sonic) gas-flow, ransverse-discharge (TFTD) geometry, utilizing either modular or monolithic designs. For C excited systems, operating at pressures ≥30mB, preionization of the largest cross-section ischarges has been necessary - using either electron-beam[1-2], silent-discharge[3] or hotoionization[4] techniques. For the alternative fast-axial-flow (FAF) systems, in which he gas flows at near-sonic velocities along the optic axis of the laser, flow-turbulence as commonly been utilized to diffuse incipient DC glow-to-arc instabilities[5-6].

Potential advantages of AC or RF (rather than DC) electrical excitation of such systems ave been advocated for some time (see, for example, literature cited in references 7,8,9). hey include greater discharge stability, power density and uniformity (without the need for uxiliary preionisation techniques); extended gas/component lifetime; avoidance of resistive allast losses; ease of modulation; and (at rather lower powers) the possibility of large rea conduction-cooled (i.e. zero or low gas-flow) designs[10-11]. Disadvantages are echnological, depending on the frequency chosen[12], and range from the bulk of the quipment or efficiency of the generator to the problems of matching to a ariable-impedance plasma, or radio-frequency interference with ancillary micro-electronics tc.

Circular symmetry of the laser beam is often considered desirable for multi-axis (e.g. -Y) machining operations. Intuitively one would expect any gain dependence on gas-flow to lter the symmetry of a TFTD system (relative to most longitudinally-excited FAF eometries). However, solid output windows can also introduce thermally-induced optical istortions at high output powers, and it is important to consider (and measure with dequate time-resolution[13]) the output characteristics of the complete laser and eam-delivery system.

For many applications a 'short-fat' high Fresnel number TFTD all-mirror laser operating ith an aerodynamic window may well out-perform a FAF laser of comparable power operating ith transmissive optics in a 'long-thin' (low Fresnel number) optical resonator.

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Table 1. (Illustrative) High Power CO$_2$ Lasers

Manufacturer	P (kW)	Exc.	η_D (%)	P_g (mB)	Beam Dia. (mm)	Output Power Density (W/cm^3)	Window	Geometry
Comb. Eng.	15-25	DC/eb		100		~3	A/d	TFTD
UTRC	18-22	DC			50	1.8	A/d	TFTD
Mitsubishi	20	DC/SAGE	16	106	80	1.7	KCl	TFTD
Majestic	20	DC/PIE	14	40	90	0.3	ZnSe	TFTD
Hitachi	20	DC	25	37	90	5	ZnSe	FAF
Ferranti	10	DC	14	50	42	2.4	A/d	TFTD
Lebedev	10	DC/eb	13	100			KCl	TFTD
MLI	9	AC			70	~1	ZnSe	TFTD
Siemens	5	RF	16	125	30	~5		FAF
Ferranti	5	DC	16	60	~20	3	ZnSe	FAF

η_D = Discharge efficiency
P_g = Gas pressure

SAGE = silent discharge assisted DC glow excitation
PIE = photoinitiated, impulse-enhanced, electrical excitation
A/d = aerodynamic window

3. FLUCTUATIONS

Although spatial averaging along the optical path is often used to achieve greater beam uniformity in either TFTD[14] or FAF types of geometry, gain variations and turbulence in gas flows can affect the beam profile and create phase, intensity, or polarisation fluctuations in the laser beam.

3.1 Gain variations

The small signal 10.6μm gain decreases as the gas temperature rises in the flow direction. In transverse flow geometry this produces a non-uniform beam profile with an axis of symmetry defined by the velocity vector. For axial flow lasers, the degree of rotational symmetry depends on the excitation; for transverse RF discharges the main effect is an enhanced gain near the wall, favouring 'doughnut' (TEM$_{01}$*) mode generation, although the intensity distribution will no longer be fully circularly symmetric. There will also be a radial (rather than transverse) density gradient, introducing thermal lensing and higher order phase changes (aberrations) in the laser beam. 2D Fresnel diffraction codes have therefore been applied fairly extensively to studies of mode generation and beam quality, following the pioneering work of Siegman and Sziklas[15] in this field. For example, recent studies of scaling of high power lasers by Bohn and Hall[16], and earlier work on the design of a multi-pass cavity for a transverse flow device[17], illustrate the importance of gain saturation and density variations across the laser aperture. At Culham we too have carried out numerical simulations of laser beam characteristics, concentrating as a 'bench mark' on modelling the behaviour of our 5kW and 10kW systems (CL5, CL10) for comparison with their observed beam profiles and far-field intensity distributions. In particular, the effect of transverse gain and saturation intensity variations on the beam profile, and of misalignment (by pre-determined amounts) on the far-field intensity, have been modelled and compared with their observation[18]. The intensity in the focal plane shows a three-lobed pattern surrounding the central 'spot' (Fig. 1).

3.2 Polarisation

It is well known that laser surface heating of some metals[19] and the related cutting efficiency can both be strong functions of polarisation[20]. Circularly polarised laser beams are therefore normally employed in X-Y cutting applications. Where laser welding is concerned, however, the situation is less clear - generally the polarisation of the laser beam is considered less important in 'keyhole' welding, although recent results for 2kW operation show good correlation between penetration depth and polarisation for 3mm wall steel tube[21].

The polarisation dependent reflectivity of metal slots[22] suggests that welding with wire-filler could also show such correlations. Thus a potential hazard of laser processing is the inadvertent coupling of the laser resonator with the workpiece, when the output will be influenced by the (variable) reflectivity of the surface. This can give rise to polarisation changes and fluctuations in output power. For example, we have shown that some 10-20% of the total radiation can appear in the orthogonal plane during welding with a linearly polarised laser source. Also fluctuations are observed in the polarisation associated with the welding process. These effects have been successfully controlled in recent work at Culham.

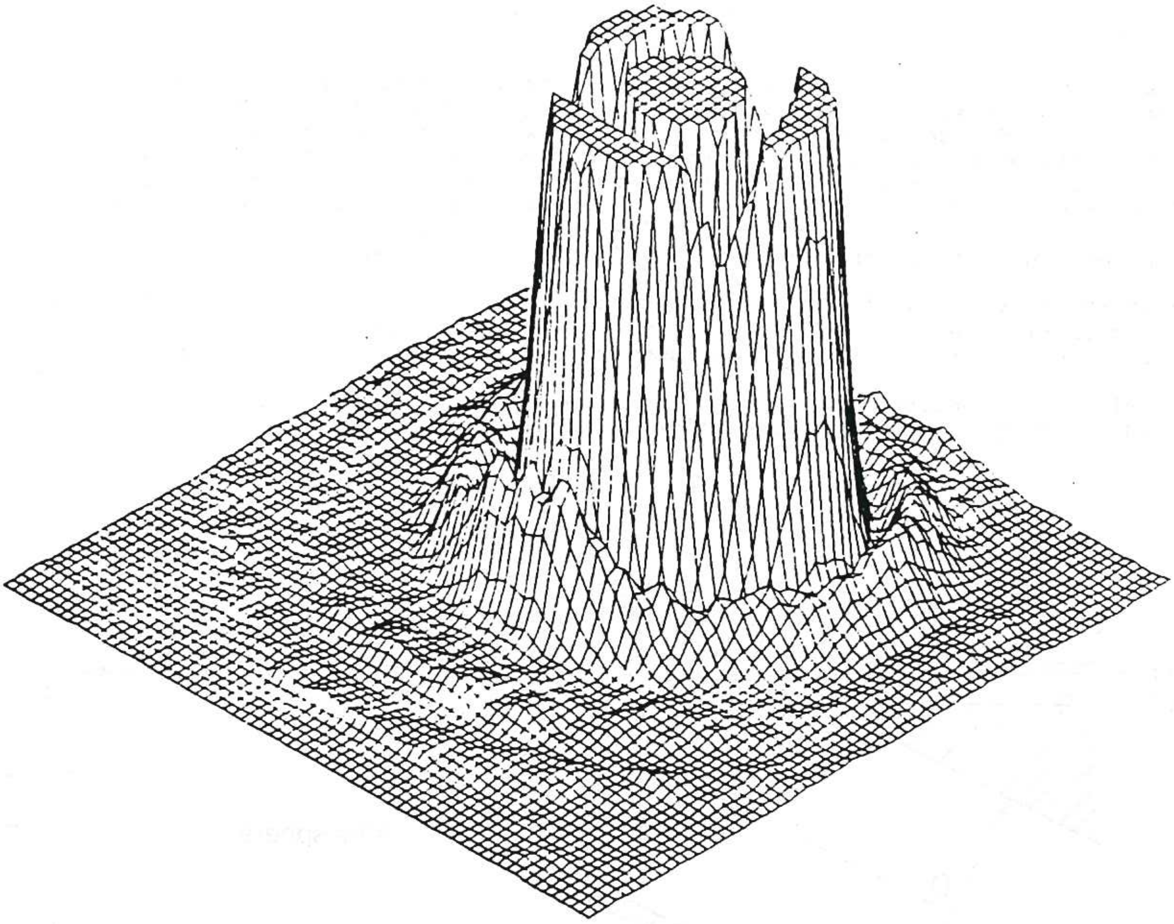

Figure 1. Computer modelling of laser beam intensity for Culham's 5kW TFTD CO_2 laser (CL5). The vertical axis plots (truncated) intensity as a function of radius in the focal plane.

3.3 Turbulence, and aerodynamic windows

Pressure and density fluctuations correlated with turbulence in the gas flow are particularly important in fast axial flow lasers, where the relatively large pressure differential required to drive the gas mix at fractional sonic speeds ($V \sim 0.5V_s$) causes medium strength turbulence levels over the full beam path, and in aerodynamic window devices.

The latter have been developed to overcome the thermal distortion and high power limitations of solid transmissive windows for laser outputs of 10kW or more. In order to maintain the pressure differential between the atmosphere and the low pressure (50mB) helium-rich laser cavity, strong differential pumping is needed to prevent air entering the discharge chamber. As a result of both density fluctuations and refractive index gradients induced in the flow by air-expansion and gas-mixing, phase fluctuations will be introduced in the transmitted beam and the 'optical quality' degraded by an amount dependent on the turbulent flow regime. Attention must clearly be given to this in designing the aerodynamic window for any high power lasers, where the effect of such fluctuations on beam quality can be evaluated via the Strehl ratio. This places a strict quantitative limit on the product of beam path, scale length and strength of the turbulent flow.

Following Bogdanov[23] and Sutton[24], the mean square random phase error imposed on a coherent beam traversing a medium containing isotropic, homogeneous fluctuations of refractive index can be expressed as

$$\langle \phi^2 \rangle = 2k^2 \langle (\Delta n)^2 \rangle \Lambda L$$

where k is the wavenumber, $\langle (\Delta n)^2 \rangle$ the mean square refractive index fluctuation, $\Lambda \ll L$ the scale size of the turbulence and L the width of the turbulent flow. Recalling that the effect of phase fluctuations is to degrade the intensity I_o (in the far field) of the transmitted beam, we may evaluate the effect of the aerodynamic window in terms of the Strehl ratio

$$S = \frac{\Delta I}{I_o} = 1 - \langle \phi^2 \rangle$$

Thus, loss of intensity in the focal plane can be related directly to the strength of the turbulence (characterised by $\langle (\Delta n)^2 \rangle$, the width of the turbulent layer L and the scale size Λ. Aerodynamic window design is ideally concerned with reducing one or more of these quantities, while balancing the desire for 'good' beam quality with minimal gas consumption, pumping capacity etc. For example, a 'free vortex' subsonic window design described by Avidor[25] was found to yield a high value for the predicted Strehl ratio, viz S=0.97 (based on interferograms obtained in the absence of a high power laser beam). This represents only 3% drop in peak intensity, compared with 10% for an earlier design.

Since it is extremely difficult to predict the turbulent flow for a given design, it is necessary to observe certain general principles aimed at minimising $\langle \phi^2 \rangle$, the mean square phase fluctuation, while optimising the pumping requirements. These are to:

i. minimise the optical path of the laser beam in the turbulent flow.
ii. reduce the pumping speed for a given pressure differential.

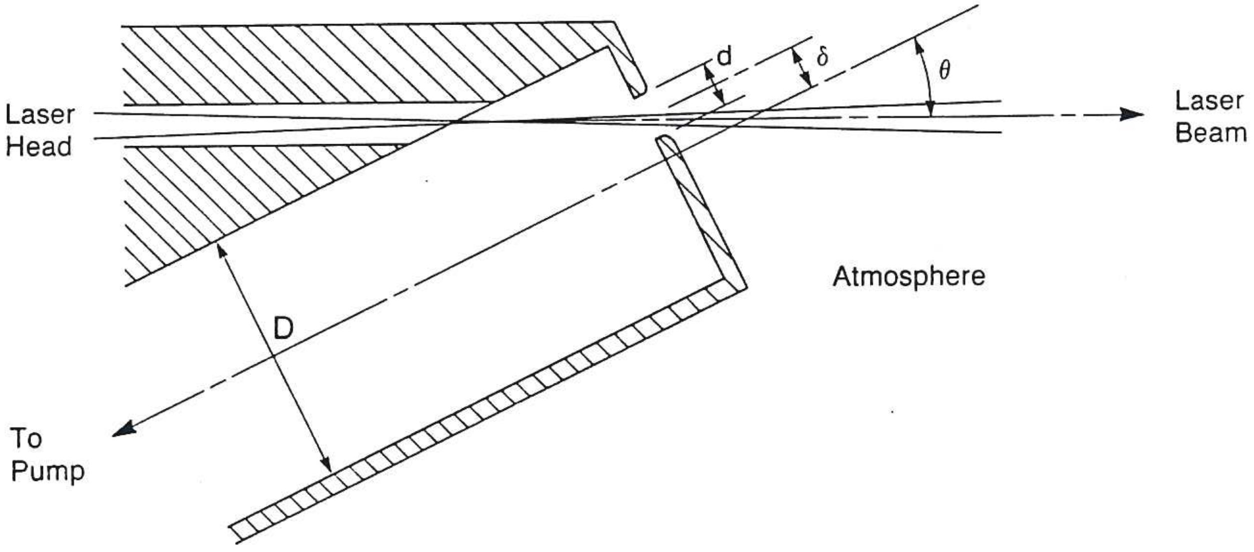

Figure 2. Subsonic 10kW aerodynamic window, schematic.

In one realisation of Culham's aerodynamic window design for CL10[26], this is achieved by arranging the axes of the air flow and laser beam at an acute angle (typically 25 degrees), and displacing the beam axis by an optimum distance from the axis of the pumping port (~0.2D, where D is the diameter of the chamber - Fig. 2). These measures allow a laser gas pressure of 50mB to be maintained for a pumping speed of 5500 litres/minute. The parameters for this particular design are given in Table 2. The nominal aperture is 5mm diameter, and the consumption of laser gas 300 litre atm/hr. As a result of the high optical quality, 85% of the laser power can be focused in a 0.5mm diameter 'spot' using f/8 spherical optics[27]. Such windows have been run successfully for ~ 6000hrs at the 10kW level, with no noticeable adverse effects on laser operation. Other designs may have a higher gas consumption - especially those using a compressed air/gas supply and/or a longer beam path in the turbulent region, which will naturally degrade the optical performance and increase the overall running cost of the laser system.

It should be noted that some enhancement of laser gas consumption is the price paid for using any aerodynamic window. On the basis of gas-chemistry measurements on a sealed-off 5kW (CL5) laser we would expect significantly lower gas consumption if a reliable, non-distorting, solid window were available at 10kW.

Table 2. CL10 Aerodynamic Window

Aperture	5mm
Cavity pressure	50mB
Pump Speed	12,000 litre atm/min
Gas consumption	300 litre atm/hr
Transmission	> 95%
Focal spot*, at f/8	0.5mm diameter

* Containing 85% of output at 9.5kW

4. PRACTICAL APPLICATIONS

Surface heat treatment makes least demand on laser pointing stability, and on the brightness of the laser source. However, it should be noted that high multikilowatt powers are necessary for 'single-shot' treatment of larger areas; low-distortion transformation hardening requires fluxes of a few kilowatts per cm^2, and use of CL10 has been demonstrated to create, in a single pulse on steel components, 40mm diameter circular hardened zones having uniform 0.5mm depth. Beam-tailoring here can rely on external integrating optics. In contrast, welding and cutting normally require excellent spatial mode control. Many materials-processing applications are sensitive to fluctuations in these parameters[13]. As an illustrative example of what can already be achieved with a high brightness laser (>4TW/m^2/steradian averaged over 85% of the enclosed power), Fig. 3 plots welding speed as a function of penetration using Culham's TFTD CO$_2$ laser CL10. Also shown are typical profiles of single-pass autogeneous butt-welds and two-pass welds made with filler wire, for a variety of different steels[28-30]. All the welds were made using an aerodynamic window, with the exception of the 11kW weld shown for API X60 which was made at lower brightness. Each was produced with the orientation illustrated, i.e. in either downhand or sidehand attitude, with a variety of different off-axis spherical focusing mirrors and powers incident at the workpiece. Cutting has also been demonstrated (but not optimized) in steels of up to 75mm in thickness. In related work we have propagated with low loss 10kW beams over a distance of 44m, and 5kW beams with a transmission greater than 85% over a distance of 75m, without servo control on any of the mirrors. Good welds have also been demonstrated at these distances. This work demonstrates that fluctuations of the type discussed in section 3 can be adequately handled both in the laser and beam lines; however, active servo control may be warranted for specific production-line applications, and such techniques are currently being investigated.

It is instructive to compare the performance of such (mainly continuous-power) CO$_2$ lasers against data recently reported for an experimental multikilowatt (average-power) Nd:YAG system which utilizes computer controlled switched-mode power supplies and pulse-shaping. Fig. 4 shows the maximum weld penetration experimentally achieved in steel as a function of incident laser power for pioneering 90kW CO$_2$ gas dynamic lasers etc.[32], the high-brightness cw CL10 laser [27] and a state-of-the-art pulsed Nd:YAG laser[31]. It should be particularly noted that the steels are not identical between these sets of experiments. However, it is noteworthy that the 2.3kW average power Nd:YAG laser, operating at a wavelength of 1μm, has achieved penetrations as high as 15-25mm[31] - albeit at a peak power certainly higher than that of the 10-11kW 10μm laser, and at welding speeds likely to be much lower (for comparable metallurgical weld quality). For example, the pulsed 1μm wavelength is claimed to produce good quality welds in 3.3mm mild steel at an averaged power input of 1.2kW (364W/mm depth) and speed of 13mm/s;[31] comparable speeds for a 5kW CO$_2$ would exceed 120mm/s.

Equally interesting is the 400W Nd:YAG laser's cutting performance on 0.7mm mild steel, after delivery through a single fibre. Cutting is achieved at 50mm/s (at 570W/mm depth delivered); 1710W/mm, delivered through three fibres, achieves a cutting speed of >167mm/s. Although these speeds are comparable to air assisted, low-order mode continuous FAF CO$_2$ cutting[33-34], cf. Fig. 5, the additional versatility of cutting reflective metals such as 6mm aluminium with good edge quality [31] is impressive. This versatility is attributable to stronger room temperature absorption of the 1μm radiation; weaker plasma effects, and the availability of high brightness pulses. (Pulse versatility[35] is, of course, also available from some CO$_2$ lasers, including a few listed in Table 1. For example, Integrated Laser Systems claim cutting of 6-10 mm Al alloy at speeds of 3.3-1.7mm/s, using a pulsed PRC 1.5kW CO$_2$ laser).

In general where a high power high brightness CO$_2$ laser can tackle a heat treatment, cutting or welding job effectively[36] its life time, higher electrical efficiency and greater available average power would seem to give it considerable advantage for specific mass-production applications. However, Nd:YAG is now demonstrating increasing versatility, and hence competition, for applications where either wavelength is acceptable and the highest process speeds are not required.

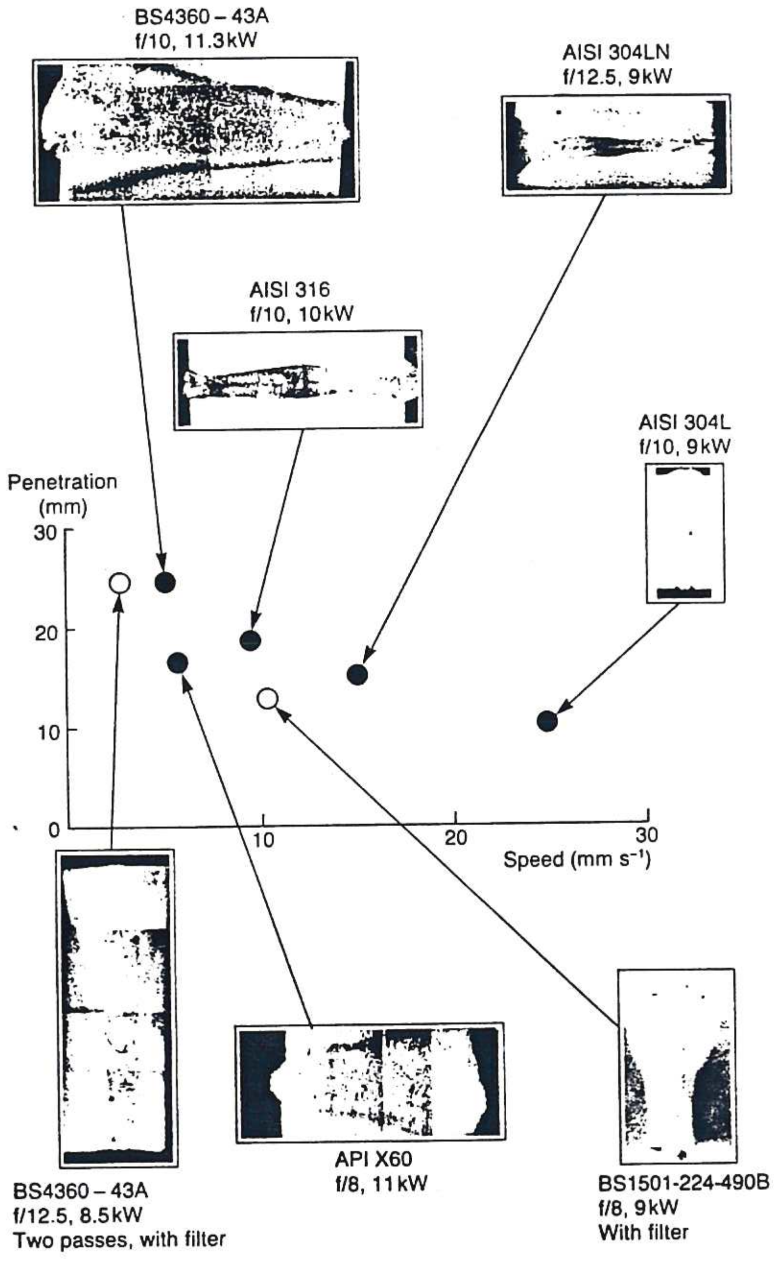

Figure 3. Weld profiles and speeds achieved with Culham's TFTD 10kW CO_2 laser CL10. (Brightness ≳ 4TW/m2/steradian at 10kW).

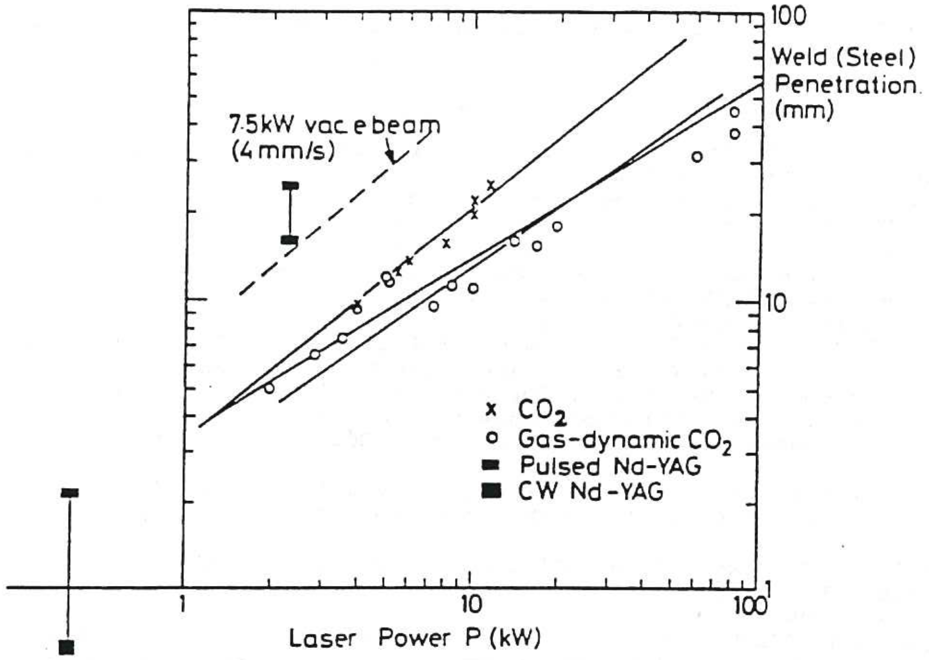

Figure 4. Maximum weld penetration scaling with average laser power: TFTD CO_2 data from Ref. 27; early gas dynamic CO_2 etc. Ref 32; pulsed Nd:YAG Ref. 31.

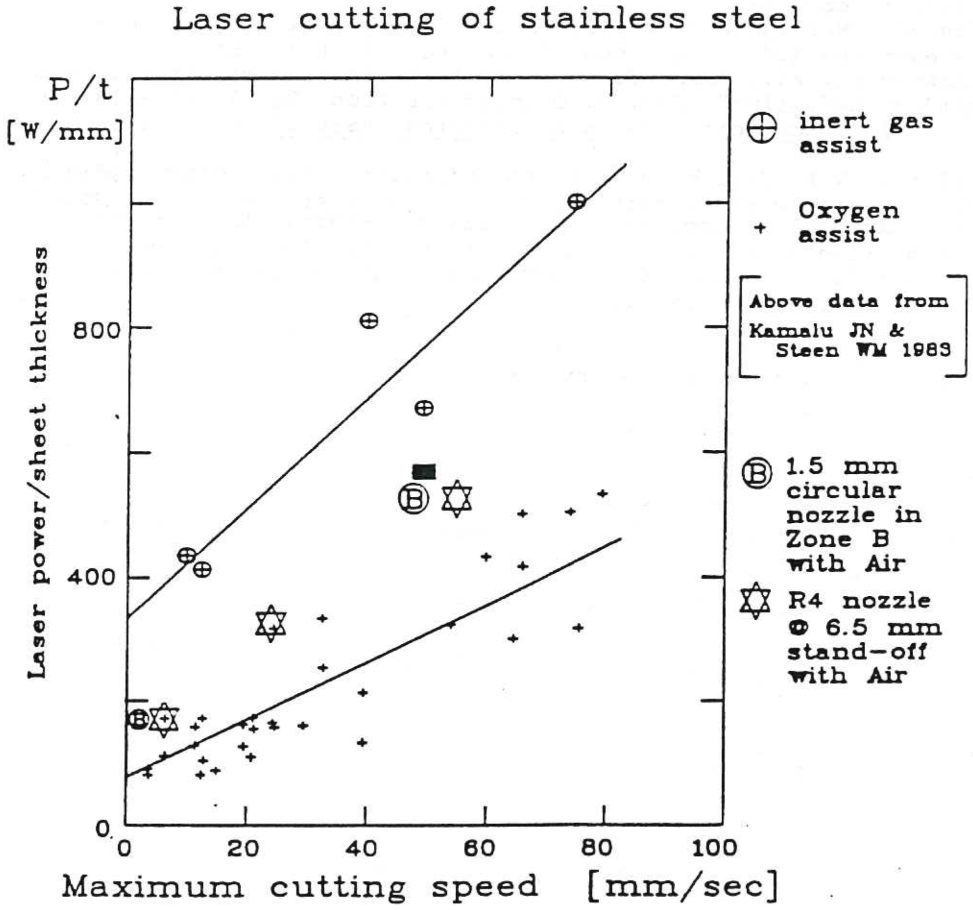

Figure 5. CW CO_2 laser gas-assisted cutting of stainless steel[33-34], compared to pulsed Nd-YAG cutting of 0.7mm mild steel[31] (result shown as rectangle).

5. ACKNOWLEDGEMENTS

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