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IMPROVED WELDING PENETRATION OF A 10kW INDUSTRIAL LASER

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Improved welding penetration of a 10-kW industrial laser

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The weld penetration of a multikilowatt CO_2 laser has been increased by reducing the laser beam divergence. This near diffraction limited laser has now demonstrated that CO_2 lasers are capable of full-penetration welding of 1-in. steel with typically 11 kW on the work. Bead-on-plate tests combined with previous data indicate that the penetration scales with laser power as $P^{0.8}$.

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Keyhole welding of metals by multikilowatt CO_2 lasers has been investigated widely at powers up to 90 kW. Much of this work has been summarized by Banas,[1] who concluded that over a wide range of power, the maximum penetration in steel was typically 19 mm using industrial lasers up to 20 kW. The Culham 10-kW cw CO_2 laser (designated CL10) described by Kaye *et al.*[2] achieved a maximum penetration of 19 mm at 11 kW. The beam quality of this laser at high power has now been further improved with a consequential further increase in weld penetration.

The CL10 laser utilizes an unstable resonator with a magnification of 3 and a diameter of 43 mm. The cavity is folded once by a rooftop reflector and uses water-cooled metal mirrors throughout. With the initial laser design the output beam was close to diffraction limited up to around 7 kW, but was increasingly degraded by thermal distortion at higher power. The sources of this distortion have now been systematically eliminated.

The intensity distribution now produced in the farfield has been measured by monitoring the power transmitted through a range of apertures from 2–10 mm diameter in a copper plate located in the focal plane of a 4-m focal length mirror. The results at 10.5 kW are presented in Fig. 1, together with the theoretical distributions for an $M = 3$ annulus and for a Gaussian truncated at 1.3 times the $1/e^2$ diameter. The measured diameter at, say, the 83% enclosed power level, is within 50% of the theoretical $M = 3$ value, and within about a factor 2 of the Gaussian diameter. The beam is plane polarized.

The capability of this beam in keyhole welding has been assessed by a series of bead-on-plate runs on 316 stainless steel and 0.2% carbon steel. The beam line from the laser to the focus included a total of five mirrors. Off-axis spherical mirror focusing was used at a beam offset angle of 3–5°, depending on focal length, the offset being in the plane of the weld. Apertures ranged from $f/10$ to $f/20$. Carefully optimized, but otherwise standard proprietary plasma control techniques were used with helium gas. Weld trials were carried out horizontally to avoid drop-through on the thicker sections, and the plane of polarization was aligned in the direction of weld.

The focus position, plasma control, and focal length were optimized using full-penetration runs on 19-mm stainless steel at 10 kW on the work. Subsequently, a series of blind bead-on-plate runs in 25-mm-thick 0.2% carbon steel were carried out at a series of speeds from 30 down to 5 mm/s. The plate was sectioned and etched and the maximum penetration measured, ignoring the very sharp spike which frequently appeared at the root. This process was repeated for a range of powers from 10 down to 4 kW on the work.

The optimum aperture on the 19-mm steel at 10 kW was around $f/10$; this was retained for all subsequent trials. Aberrations due to the off-axis focusing are calculated to produce a blurr spot diameter of $200\,\mu$, whilst the unaberrated focal spot diameter was typically $600\,\mu$ at 83% enclosed power, based on Fig. 1. As the aberration is astigmatic, a line focus is produced 2 mm either side of focus, which may have ess effect than the blur spot diameter would suggest.

An optimized weld in 19-mm stainless steel is shown in Fig. 2. The weld is seen to be very narrow and parallel sided. The results of the bead-on-plate trials are summarized in Fig. 3, where penetration is plotted against weld speed. It is observed that the penetration increases slowly with decreasing speed. Also shown are the equivalent results at 7.5 kW of Konkol *et al.*[3] using a vacuum *e*-beam. Whilst the results are similar at high speed for this same power on the work, the *e*-beam penetration increases much more rapidly at slower speeds. When cross plotted against power P, the data of Fig. 3 give a scaling of penetration as $P^{0.8}$ at constant speed.

The minimum speed at which it proved possible to maintain a stable keyhole was 4–5 mm/s. The maximum penetration achieved is compared with a collation by Banas[1] of previously published data in Fig. 4. It is clear that the present results extrapolate smoothly from the data previously published for powers up to 5 kW, and are substantially better than previously achieved at the higher powers. A scaling as $3.3P^{0.8}$ is also shown in Fig. 4 and is seen to better fit the present data and that at lower power than does the $P^{0.7}$ scaling of Banas[1] or the $3.7P^{0.6}$ scaling of Megaw and Kaye.[4] Typical *e*-beam results at similar speed (4.2 mm/s) obtained by Konkol *et al.*[3] are also shown in Fig. 4. Whilst the maximum laser penetration is typically half that achieved by vacuum electron beams of the same incident power, the scaling of penetration with power is similar.

The CL10 laser is operated routinely at 10 kW, and will operate in excess of 12 kW for times sufficiently long to enable systematic weld trials. Extrapolating the present data up to the maximum power of 11.3 kW delivered to the workpiece suggests a maximum (blind) penetration of 23 mm. In practice, the penetration achieved is a little higher for full-penetration welds, and it has been found possible to fully penetrate 1-in carbon steel plate at this power. A section of such a weld is also shown in Fig. 2 above. On the basis of the data of Swift-Hook and Gick,[5] the sectional area corresponds to a coupling efficiency of about 75%, whilst the penetration power of 440 kW/m is much less than previously reported for laser welding at this thickness.

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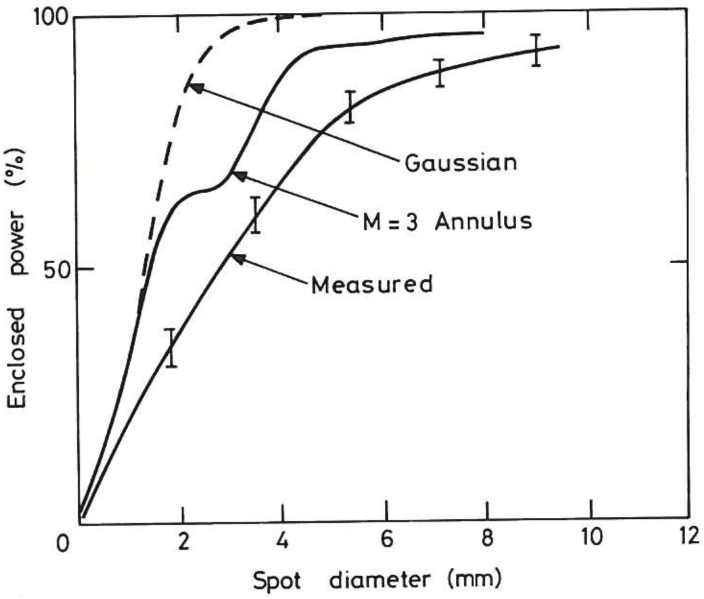
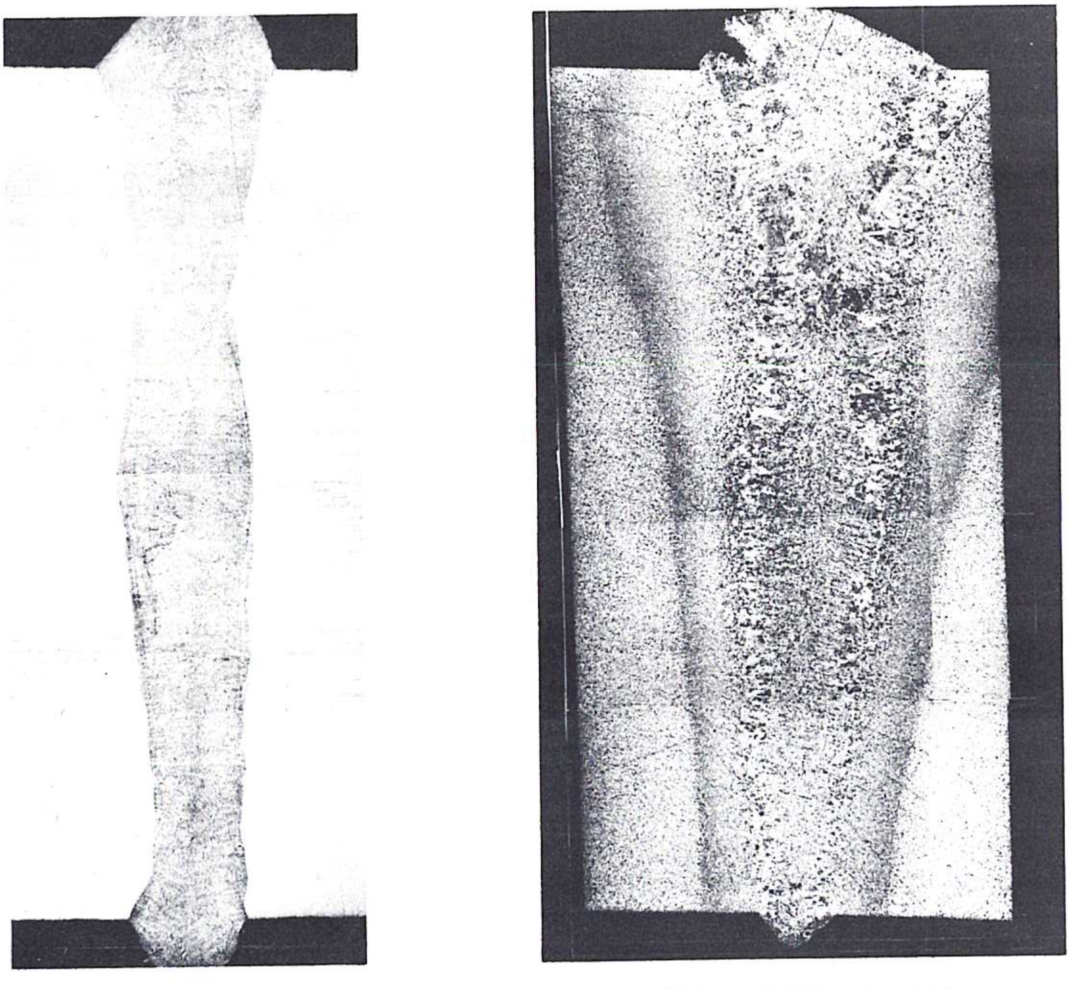


Fig. 1 Measured enclosed power in the focal plane at 10·5kW compared with computed results for an $M=3$ annulus and an optimized apertured Gaussian.



19mm, Type316 stainless steel
10kW, 9mm/s, $f/10$

25·4mm, 0·2% carbon steel
11·3kW, 5mm/s, $f/10$

Fig. 2 Weld sections.

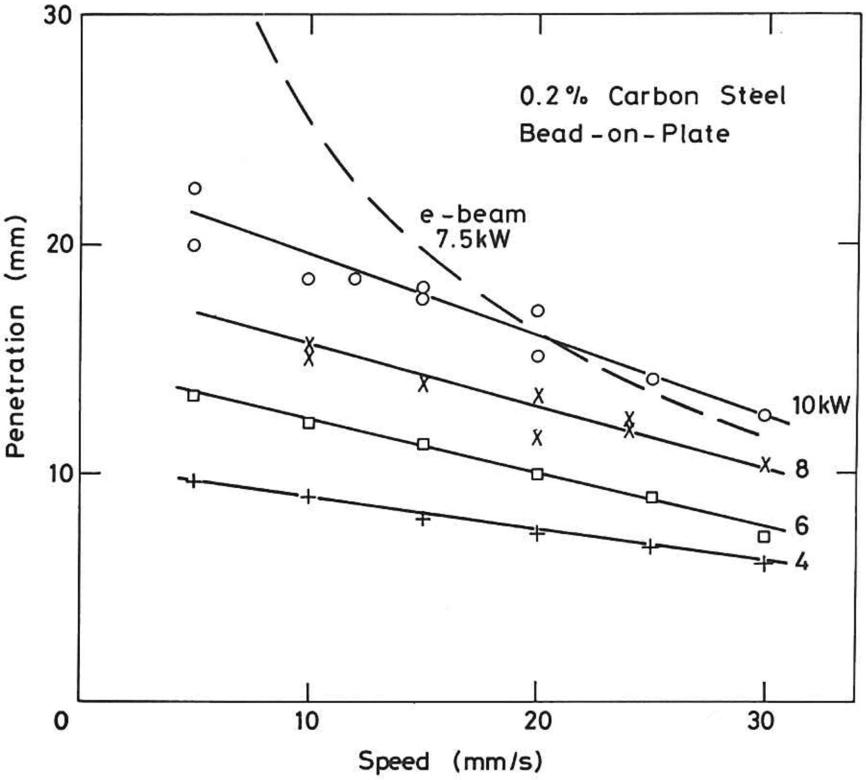


Fig.3 Measured dependence of penetration on weld speed over a range of laser powers for blind bead-on-plate runs on 0·2% carbon steel; *e*-beam results of Konkol[3] are also shown.

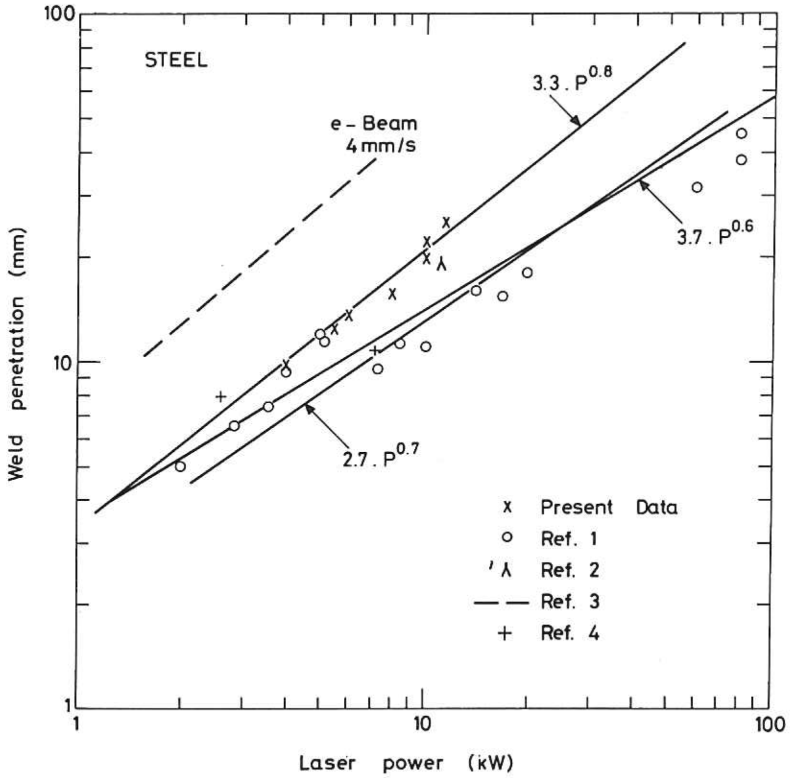


Fig.4 Maximum weld penetration scaling with laser power.