UKAEA

Preprint

LASER WELDING OF STEEL PLATES WITH UNMACHINED EDGES

J. H. P. C. MEGAW
M. HILL
R. JOHNSON

CULHAM LABORATORY
Abingdon Oxfordshire

1981

CLM-P649

LASER WELDING OF STEEL PLATES WITH UNMACHINED EDGES

by

J.H.P.C. Megaw, M. Hill and R. Johnson*

UKAEA Culham Laboratory, Abingdon, Oxon, OX14 3DB,
*UKAEA Springfields Nuclear Power Laboratories, Salwick, Preston, PR4 ORR

ABSTRACT

Laser welding of assemblies from sheet metal will be simplified if the joint edges need not be accurately machined or indeed if the component parts are laser trimmed before joining. However, the joining of unmachined edges by laser poses some novel features, and this paper describes work carried out using the Culham Laboratory 5kW CO_2 laser CL5 to investigate these. The material used was principally 6 mm mild steel, a material known to present problems in electron beam welding. The edges to be welded were formed by both mechanical cropping and laser cutting, and welding was carried out with close-fitting and deliberately spaced joints. Effort was devoted to investigating a variety of filler techniques and to developing the use of automatic wire feeding equipment. This was found to successfully control all problems associated with parent plate composition, edge finish and gap spacing. Metallurgical examination and mechanical tests so far performed have confirmed that strong, high integrity welds, having minimal distortion were routinely achieved.

To be published in the proceedings of the Institute of Metallurgists Conference:
Joining of Metals - Practice and Performance;
University of Warwick, 10th-12th April 1981.

JULY 1981

INTRODUCTION

The concepts and applications of cutting and welding by laser are now fairly familiar. Thus, in addition to tackling a diversity of non-metal workpieces, the laser is now recognised as an economical means of precision profile cutting metal up to several millimetres thick. In welding, interest is growing in step with the increasing availability of higher power lasers. The process, with its deep penetration mechanism, can probably be most readily exploited in the joining of high precision, fully-machined components, and much effort is now being devoted to the development of laser welding of components related to such industries as aerospace, automotive and nuclear. In contrast, the motivation for the work described in this paper was the use of a laser in the manufacture of assemblies from sheet metal, where fabrication will be simplified if the edges to be joined need not be accurately machined; indeed there are considerable attractions to laser trimming the component parts before joining. A number of potential applications can be anticipated where the movement of a laser beam over a workpiece is used to trim two edges, which are then indexed together and welded by a subsequent pass of the same beam. Specific examples might be the fabrication of box structures, or the joining of strip in a strip-mill.

Although these ideas have been widely discussed for some time there are few published accounts of systematic investigations. The problems have long been recognised: guillotined or laser-cut edges may be oxidised (to the detriment of the subsequent weld) and, by not being flat, will present a joint gap. The laser beam may pass through the gap without depositing sufficient energy to achieve adequate fusion; even if it does, the shrinkage of metal will result in a weld of notched cross-section. Therefore, the aims of this work were to explore these problems, and ways of tackling them, particularly through the use of filler.

The material chosen for the work was 6mm thick weldable structural steel plate BS4360 grade 43A. This composition and thickness are extensively employed in a very wide variety of engineering applications, the high volume being potentially well suited to the high productivity of a laser. The 6mm thickness is very comfortably within the single pass penetration capability of a 5kW laser, but structural steels are known to present problems of porosity and solidification cracking in high power-density, autogeneous welding processes. The porosity is normally attributed to the oxygen level in the parent plate; for example, the electron-beam welding of semi-killed and rimming steels requires care, and beam oscillation and reduced welding speeds have been found beneficial. Porosity has been reported by Parrini et al(1) in the laser welding of API steels X65 and X70 (0.26%C, 1.40%Mn and 0.23%C, 1.6%Mn respectively). Solidification cracking (associated with formation at the grain boundaries of low melting-point compounds, predominantly those of sulphur and phosphorus) is reduced in electron beam welding of structural steels by use of low-restraint joints and low welding speeds. Russell(2) has studied the influence of impurities on solidification cracking in carbon-manganese steels during electron beam welding. In the present work, the use of filler was therefore of interest not only for geometric control in, for example, filling the gap, but also for possible compositional control to reduce or eliminate porosity and solidification cracking.

EQUIPMENT AND PROCESSES

Laser System

This work is complementary to that of Johnson et al(3), both studies utilising 5kW lasers model CL5 developed at Culham Laboratory, as described by Armandillo and Kaye(4) and with applications by Megaw and Kaye(5). The bulk of the present experimental work was carried out at Culham, on a laser system which incorporated three workstations, Ward et al(6). Welding was performed in one workstation, and the laser-cutting part of the trials was carried out in another.

Welding

Multikilowatt laser welding proceeds by the deep-penetration, "key-hole" mode. Although a vacuum is not required, a jet of inert gas, usually helium, is directed at the beam interaction point; this controls the plasma formed there and prevents the gross oxidation which would otherwise result. To avoid oxidation of the upper and lower beads during cooling, and to prevent entrainment of air by the plasma control jet, gas shrouds are usually provided above and below the workpiece. Details of the welding arrangements used are shown in Figure 1. The beam was focused by an ~f/6 on-axis spherical mirror system of focal length 320mm (although lens focusing could equally well have been used). The helium flow to the beam interaction region was ~40 sl min^{-1}, and the upper and lower shrouds were each supplied with an arbitrarily set helium flow of ~100 sl min^{-1}. It is conservatively estimated that the present multi-purpose shroud arrangement could be redesigned for a dedicated application to operate at less than 100 sl min^{-1} helium total. For the wide variety of edge conditions used, pairs of sample plates were clamped together on a carriage and transported beneath the beam on a 2m long linear slideway. The carriage was belt driven by a torque motor, and digital feedback from a shaft encoder was employed to provide precise control of the welding speed. Each plate was 6mm thick and 100mm wide x 300mm long, and they were welded together to produce samples 200mm x 300mm. For those parts of the trials which included the addition of filler, rod (diameter 1.6 or 3.2mm) was simply laid along the joint line on the plate surface, or wire was fed to the weld pool. A wire feed unit model WF205, designed by Redman Control and Electronics Ltd for precision automatic arc welding was used to provide accurate feed rates down to 7mm s^{-1}. Filler wire, 1.2mm diameter, was guided through a P.T.F.E. tube and directed into the pool via a stainless steel nozzle, angled at 45^{o} to the surface of the plates. Wire was fed in the same direction as the workpiece movement and opposite to the flow of gas from the plasma control jet, as illustrated in figure 1. At the beginning of every weld run the laser beam was switched on slightly before starting the wire feed, whilst at the end the wire feed was stopped before switching off the beam. The pointing accuracy required (approximately ±0.7mm) for delivering the wire to the weld pool was not found unduly demanding; this tolerance is determined by the extent of the surface plasma.

Cutting

Laser cutting is similar to laser welding except that the molten metal is removed by means of a high velocity jet of gas. Cutting speed and edge quality are influenced by the mass flow-rate of gas (which controls the removal of molten materials) and the choice of gas; thus a reactive gas will generally produce a higher cutting speed but poorer edge quality as compared with an inert gas. In this work, an f/6.4 optics system was employed, and a 1.8mm diameter jet, which could be supplied with a range of gases at pressures up to 8 bar, was used to clear the kerf.

CUTTING INVESTIGATIONS, RESULTS AND DISCUSSION

Three methods of machining were used to prepare the plate edges for the welding trials: milling, guillotining (cropping) and laser cutting. The first two were achieved by standard workshop techniques. In producing laser-cut edges, a brief investigation was made of the effect of laser power and gas assistance. Some of the results are summarised in figure 2 which plots cutting speed (threshold for full penetration) against laser power at the workpiece for three gases (helium, air and oxygen), each at two pressures. While the figure shows the dramatic increase in speed resulting from use of oxygen, it does not indicate the corresponding deterioration in edge quality. A detailed discussion of these results is outside the scope of this paper, and will be presented elsewhere. For this work, it was considered that in a production application where a single laser system would perform both cutting and welding, it would be reasonable to achieve cutting speeds comparable with those for welding (20-30mm s^{-1}), i.e. by choosing air assistance. Air has the merit of economy (compared with other gases) and of yielding a superior edge finish (compared with oxygen). Figure 3(c) is a scale drawing of laser cut edges, close-butted together.

A threshold speed of ~30mm s^{-1} was achieved during these trials for cutting 6mm steel, with ~4kW laser beam power at the workpiece. This was obtained when using the 1.8mm diameter jet supplied with air at a pressure of 2.7 bar. However, to ensure complete cut-off along the entire plate length, most of the work was carried out at speeds of ~20mm s^{-1} for air. Additionally, some samples were cut with helium assistance in preparation for welding; cutting speeds here were approximately 15mm s^{-1}. The air-cut edges appeared completely covered with an oxide layer, while the helium cut edges exhibited an almost oxide free zone down to about 1/4 depth. Below this the edge was oxidised, presumably due to the entrainment of air with the cutting jet. An EPMA of a transverse section of a typical laser cut edge did not show any pick-up of oxygen by the parent material, within the resolution of the instrument.

WELDING INVESTIGATIONS, RESULTS AND DISCUSSION

In the investigations, the following were taken as variables:

1. Plate composition: two batches of plate from different casts were used. Analyses of these, designated P1 and P2, are given in the table below. It is seen that P1 has lower carbon and higher oxygen content than P2.
2. Plate finish: black (as rolled) and sand blasted.
3. Edge preparations: milled, cropped and laser-cut with air and helium. In addition, bead-on-plate welds were carried out.
4. Joint fit-up: close butting and spaced joints.
5. Filler: three different types were employed, two as laid-on rods, F1 and F2, and one as a wire feed F3. Nominal compositions for F1 and F2 are given in the table below, together with an analysis of F3.
6. Filler supply rate; rod sizes and wire feed speed.
7. Welding speed:
8. Beam focus position with respect to plate surface.

TABLE 1 - Composition (analyses and nominal) for steel plates and fillers

Material	(%Wt)	C	Mn	Si	Ni	P	S	Cu	O_2	Other
Plate BS 4360	"Low" carbon (P1)	0.06	0.29	0.06	0.02	0.008	0.030	0.06	0.028	Al 0.01
Grade 43A (Analysis)	"High" carbon (P2)	0.12	0.45	0.14	0.11	0.017	0.041	0.37	0.008	Al 0.01
Filler Rod	BS 1453 - A1 (F1)	0.10 Max	0.60 Max		0.25 Max	0.04 Max	0.04 Max			
(Nominal)	BS 1453 - A3 (F2)	0.30 0.25	1.6 1.3	0.5 0.3	0.25 Max	0.04 Max	0.04 Max			Cr 0.25 Max
Filler Wire (Analysis)	Bostrand BW1 BS2901- A18 (F3)	0.08	1.28	0.73	0.05	0.014	0.032	0.08		Cr 0.04 Al 0.01 Mo 0.02 Nb 0.01 Ti 0.01 Co 0.02 V 0.01

Composition Effects

In autogeneous welds not involving laser-cut edges (bead-on-plate runs and the joining of machined and cropped edges), it was generally found that sound welds could be produced in plate P1, as seen for example in figure 4, but for the same conditions in plate P2, solidification cracks occurred, as seen for example in Figure 5. Such cracks are usually associated with the levels of sulphur, phosphorus and carbon, and it is indeed seen (from the table above) that these levels are higher in P2 than P1, although this is also true of the level of manganese, which helps to counteract the effect of sulphur. The relationship between crack susceptibility and composition has been investigated in submerged-arc welding by Garland and Bailey(7) and in electron beam welding(2). In that work, test plates in a range of compositions, although of constant Si level, were stressed during welding so that massive cracks developed along the weld axis. The crack length was then empirically fitted by a cracking index containing factors depending on levels of C,P,S and Mn. Whilst no such massive cracks were observed in the present laser welds, it is of interest to note that evaluation of the index shows that in both electron beam and submerged arc welding cases, the change of composition P1 to P2 would correspond to an approximately 50% increase in the crack susceptibility index value.

From a restricted number of trials, there was some evidence that in the autogeneous welding of laser-cut edges, welds of helium-cut edges contained substantial porosity (Figure 6), while air-cut edges welded satisfactorily (Figure 7). This appeared to be true for both P1 and P2, i.e. the edge condition was more important than the O_2 level in the parent plate. These results, which are not yet understood, were rather surprising, for the air-cut edges were clearly much more oxidised than the helium-cut edges.

Using plates P1 having cropped edges, a few welds were made with rod filler F1. This resulted in massive weld porosity, presumably due to the low level of de-oxidisers. A few trials with rod filler F2 on cropped edges showed satisfactory results, and the effects of its high carbon level are referred to below.

A number of trials were carried out to assess the benefits of treating the plate with an aluminium de-oxidising paint and by rotary wire-brushing the laser-cut edges; neither produced a dramatic effect. The most positive observation was that use of the latter procedure resulted in weld top beads which were slightly smoother and cleaner (although sections of welds carried out without the procedure still appeared perfectly acceptable).

Weld Geometry Effects

Figure 8 shows a typical cross-section resulting from the laser welding of cropped edges without filler. This profile is totally unacceptable because the shortage of material results in a serious reduction of final workpiece thickness, and the concave top surface of the melt is in tension during solidification shrinkage, which in high restraint could result in a tendency to centre line cracking. Laser-cut edges generally permitted closer fit-up, and sections of welds of air-cut edges appear to be quite acceptable as shown in figure 7. However, the shortage of material is more evident on inspection of the plate surfaces; the weld is very irregular and is effectively notched along its length.

The first attempt to add filler was made with pre-placed rods and cropped edges. For the fit-up shown schematically in figure 3(a), a 1.6mm diameter rod (cross-sectional area ~2mm^2) was chosen, and the result is the very acceptable profile seen in Figure 9. For the deliberately spaced cropped edges of figure 3(b), a 3.2mm diameter rod was used, welding speed being reduced to 5mm s^{-1}, and the weld section of Figure 10, although not desirable, shows that the large gap can be tolerated. However, that work highlighted the problems of filler placement and matching the volume of material supplied to that actually required by the joint gap. Further investigations therefore proceeded on cropped plates with the use of the automatic wire feeder. With an F3 wire diameter of 1.2mm (area ~1mm^2), the joint shown in Figure 3(a) would be expected to require a wire feed speed of approximately twice the welding speed. This was indeed observed to be the case for an acceptable profile, where welding speeds were found to be 11mm s^{-1} and preferred wire feed speeds were 22mm s^{-1}. The results are not shown, but instead Figure 11 shows results for laser-cut edges (joint configuration of Figure 3(c)) where, as anticipated, preferred wire feed speeds match welding speeds at 11mm s^{-1}. With deliberate introduction of a 1/2 mm gap, an acceptable weld profile (not shown) was achieved with weld speed reduced to 8mm s^{-1} and wire feed rate increased to 20mm s^{-1}. A limited number of trials were carried out to weld laser cut edges without prior removal of the adherent under-dross. Figure 12 (weld speed and wire feed speed set to 8mm s^{-1}) shows this result which appears satisfactory. The basic weld cross-section is identical to that producd when the dross is removed before welding; however, much of the dross has not remelted so that it is seen as "spikes" attached to the underbead. This additional material could be easily removed by mechanical dressing.

The effect of raising and lowering the focus mirror is shown in figure 13, which is a tracing of weld cross-sections achieved for cropped edge plate welded at 11mm s^{-1} with wire feed speed of 21mm s^{-1}. The optimum focus position corresponds to that which gave maximum penetration in a bead-on-plate weld, and it also gave the most parallel sided weld in these trials. With the focus raised 2mm from optimum, the weld cross-section is triangular with poor penetration, whilst with the focus lowered 2mm, the lower part of the weld is narrow, making alignment more critical.

Mechanical Tests

A variety of specimens from plates with cropped and laser cut edges, welded without and with filler, were assessed for hardness, strength, ductility and toughness, as well as for distortion. Hardness profile scans across weld sections at half depth were made with a Vickers microhardness tester, and are shown in Figure 14. Three profiles in part (a) show the effects of adding and varying filler when welding plate from batch P1 (low carbon) with cropped edges: with no filler, significant hardening is seen as a consequence of fast quenching in the narrow weld; with the addition of filler F3 (~0.12%C), a decrease in weld hardness results despite F3 having a higher carbon content than the plate, because of reduced quenching rates in the wider weld; use of filler F2 (~0.25%C) gives a higher hardness, but only comparable with the no filler weld for the same reason. Figure 14(b) shows little variation in weld metal hardness for cropped and laser cut edges in plate from batch P2 (high carbon), welded without and with the addition of the matching carbon filler. This is consistent with the uniformity of composition and weld width (and therefore quenching rates) in these specimens. Single point hardness measurements, made in the weld centre and parent plate regions of 12 specimens prepared for tensile testing gave values of 250 ±20 and 135 ±10 HV (30kg) respectively, in good agreement with the microhardness figures.

The tensile test specimens, taken from welds in cropped and laser cut plate, both without and with F2 and F3 fillers, were prepared with centre sections 6 x 6 mm and 36mm gauge lengths for testing on a Houndsfield Extensometer. In all cases the parent material failed midway between the welded joint and the end of the parallel section. Average yield points and tensile strengths were found to be approximately 300 and 400N mm^{-2} respectively, with an average elongation of 27% and area reduction of 55%. These values are typical for this steel and in no case did a weld fail. Similarly, 12 welded specimens were prepared 10 x 5mm (half normal height) for Charpy V-notch-testing, together with two from parent material. The tests have been so far confined to room temperature, and the impact energies required to break the welds were 50 ±20J, with those for the parent material being 62 and 65J. For comparison, the manufacturers figures for Charpy tests on 10 x 10mm specimens of undiluted filler wire were 80-120J.

Shrinkage in the samples welded without filler, and those where the quantity of filler matched the joint gap, was found to be ~0.25mm. No longitudinal ("bow") distortion was detectable above the variation of that found in the stock plate. Some "winging" was detected, particularly for the more triangular-shaped weld cross-sections as might be expected, but again was difficult to quantify in stock plate. However, with control of filler rates to produce the near parallel sided welds as shown in figure 11, angular distortion was limited to less than 0.6^{o}.

CONCLUSIONS

Satisfactory cutting performance was achieved in these trials when using air as the assist gas. Although the alternative use of high pressure oxygen yielded very significant enhancement of cutting speed, air has the merit of economy and of yielding a superior edge finish. Helium-cut edges were much less oxidised than air-cut edges but, when welded without filler, tended to exhibit weld porosity.

With the present laser welding technique the grade 43A parent material may exhibit small solidification cracks. This appears to correlate with levels (within specification) of sulphur, phosphorous and carbon. Athough modification of the technique (possibly in the manner adopted in electron beam welding) may control this, use of filler is a much more attractive solution in joints of poor fit-up. The use of automatic wire feed apparatus in conjunction with laser welding is controllable and reproducible, and "double-deoxidised" filler is found to solve all problems associated with parent plate composition, cut edge condition and plate surface condition. The mechanical tests so far conducted on the welds show excellent results. Laser welding, like electron beam welding, requires precise alignment of the beam on the joint. This should not prove to be an intractable problem since the present concept is based on cutting and welding taking place on the same equipment, on a common axis.

Discussion of economics is outside the scope of this paper, since cost-effective application in any specific area will depend on factors such as the reduction of costs through elimination of edge preparation, the ability to achieve higher speeds and degree of automation, and the reduction of distortion. It is however noted that the principal element in operating cost per hour for a multikilowatt laser cutting/welding system will be that associated with capital cost. The cost per hour for welding consumables (principally shroud gas), although possibly comparable to this element, is of course only evident during those times when welding is in progress. The cost per hour for cutting consumables (air) is negligible.

ACKNOWLEDGEMENTS

We are grateful for the assistance of S.J. Osbourn and S.P. Walde in the experimental aspects of the work, and we appreciate the interest of A.S. Kaye, I.J. Spalding and B.A. Ward (Culham), A.F. Taylor (SNPDL), and D. McKeown (BOC Murex).

REFERENCES

1. Parrini, C., Banas, C.M. and De Vito, A., 1976, "Laser-welding of pipeline steels", AIM-ASM Welding of HSLA Microalloyed Structural Steels Conference Proceedings, Rome, Italy.

2. Russell, J.D., 1977, "Development of an electron beam weld solidification crack test", Welding Institute report 47/1977/P.

3. Johnson, R., Hill, M., and Megaw, J.H.P.C., 1981, "Laser cutting for welded joints", Institution of Metallurgists Joining of Metals Conference Proceedings, Warwick, UK.

4. Armandillo, E., and Kaye, A.S., 1980, J. Phys. D, 13, 321.

5. Megaw, J.H.P.C., and Kaye, A.S., 1978, "High power lasers and laser metalworking", Fourth European Electro-optics Conference Proceedings, Utrecht, Proc. S.P.I.E., 164, 241.

6. Ward, B.A., Brown, D.P.D., and Walker, C.I., 1981, "Case study of a high power CO_2 laser system for Class I operation", S.I.R.A. Laser Safety Seminar Proceedings, London.

7. Garland, J.G., and Bailey, N. "Solidification cracking during the submerged arc welding of carbon-manganese steels", 1975, Welding Institute report M/75/73.

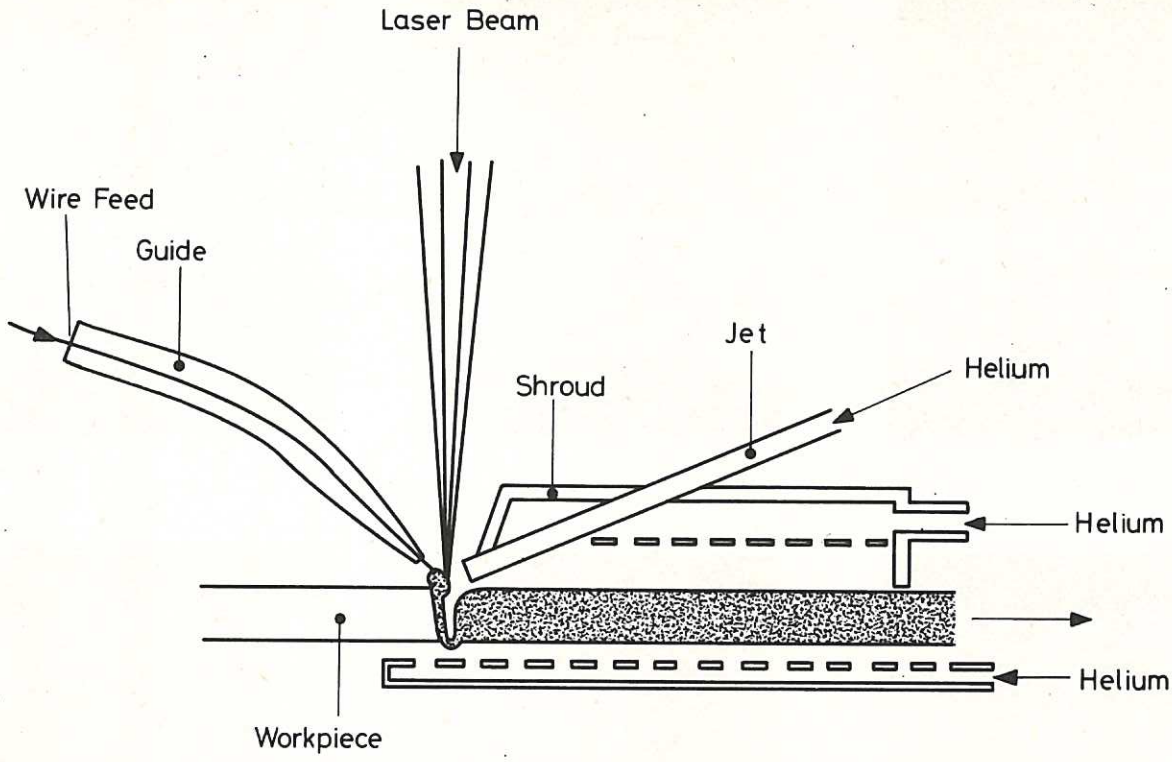

Fig 1. Laser Welding and Wire Feed Arrangement.

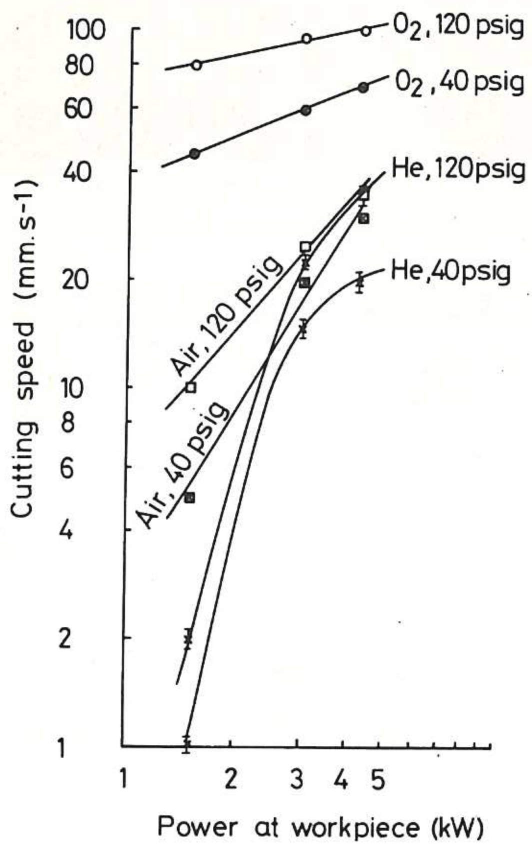

Fig 2. Cutting Speed vs Laser Power.

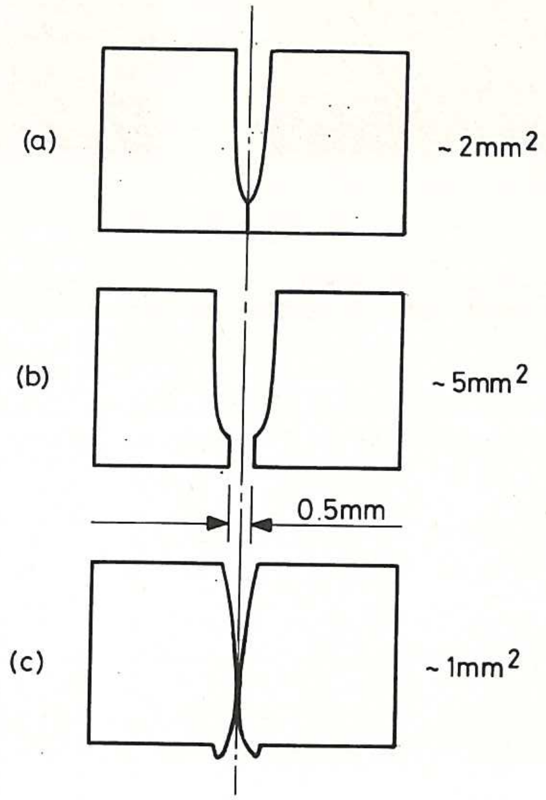

Fig 3. Variation of Joint Geometry:
(a) & (b) Cropped; (c) Laser Cut.

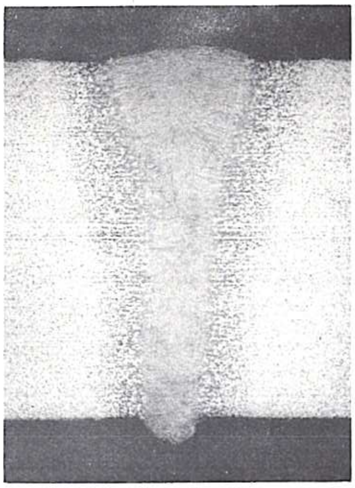

Fig 4.

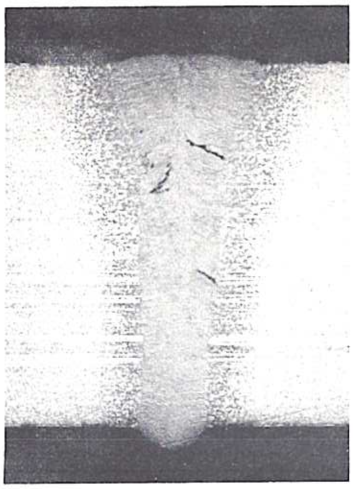

Fig 5.

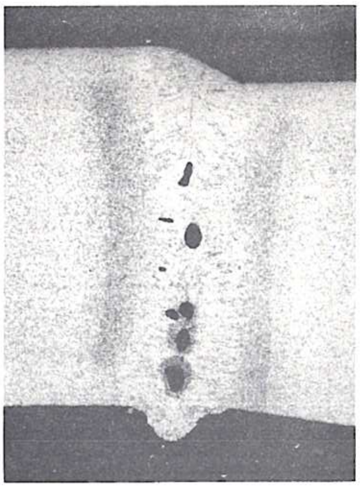

Fig 6.

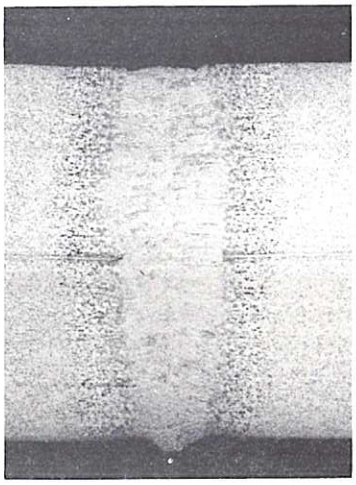

Fig 7.

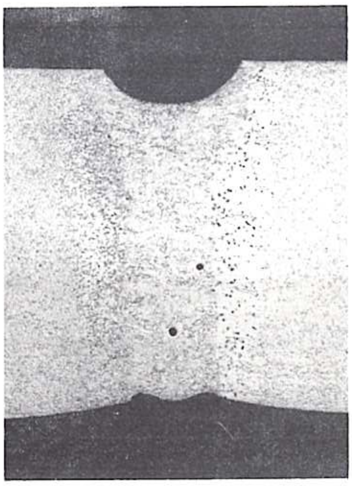

Fig 8.

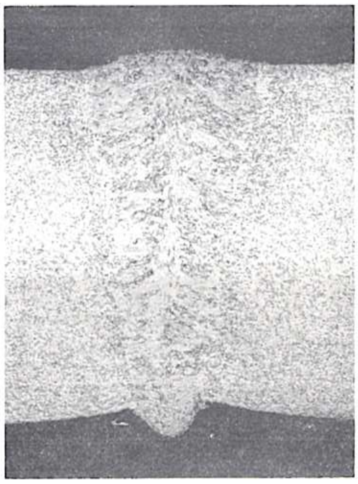

Fig 9.

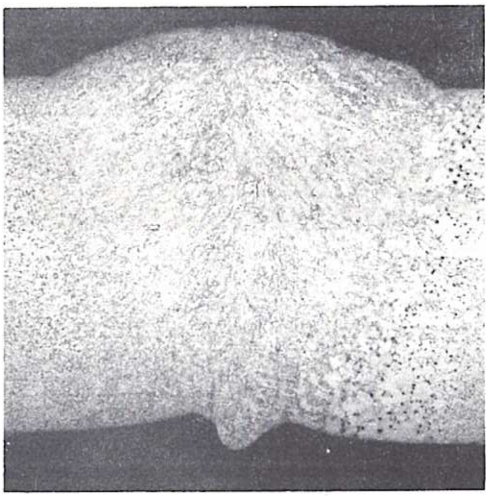

Fig 10.

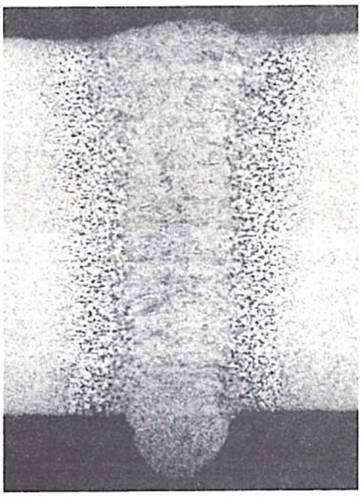

Fig 11.

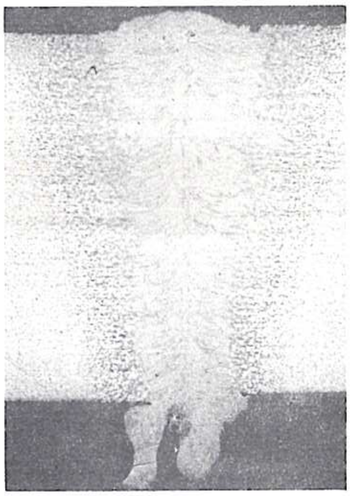

Fig 12.

Laser Weld Cross-Sections (see text for details).

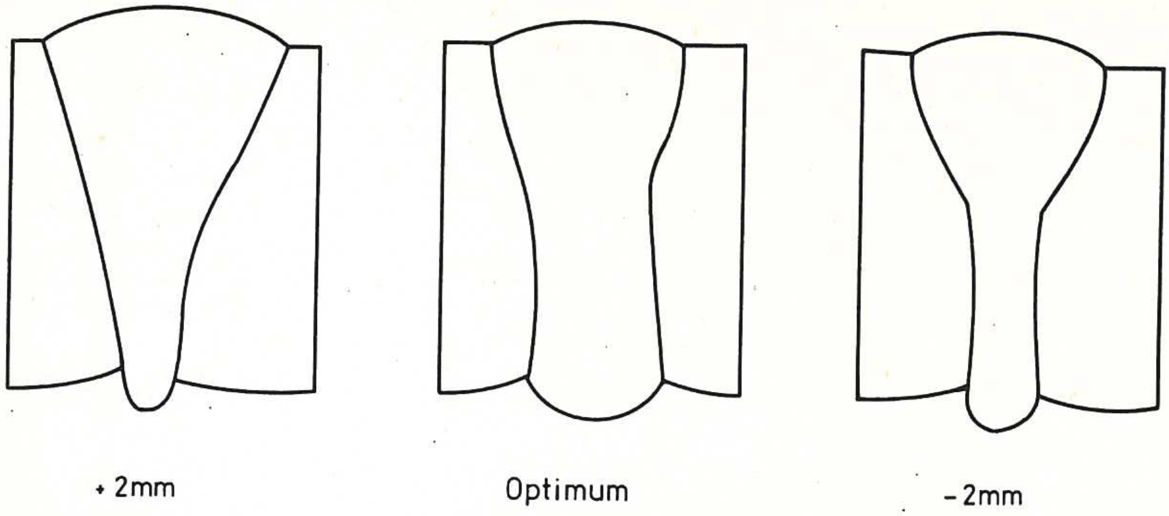

Fig 13. Variation of Laser Weld Cross-Section with Focus Position for an ~f/6 mirror (Focal Length 320 mm).

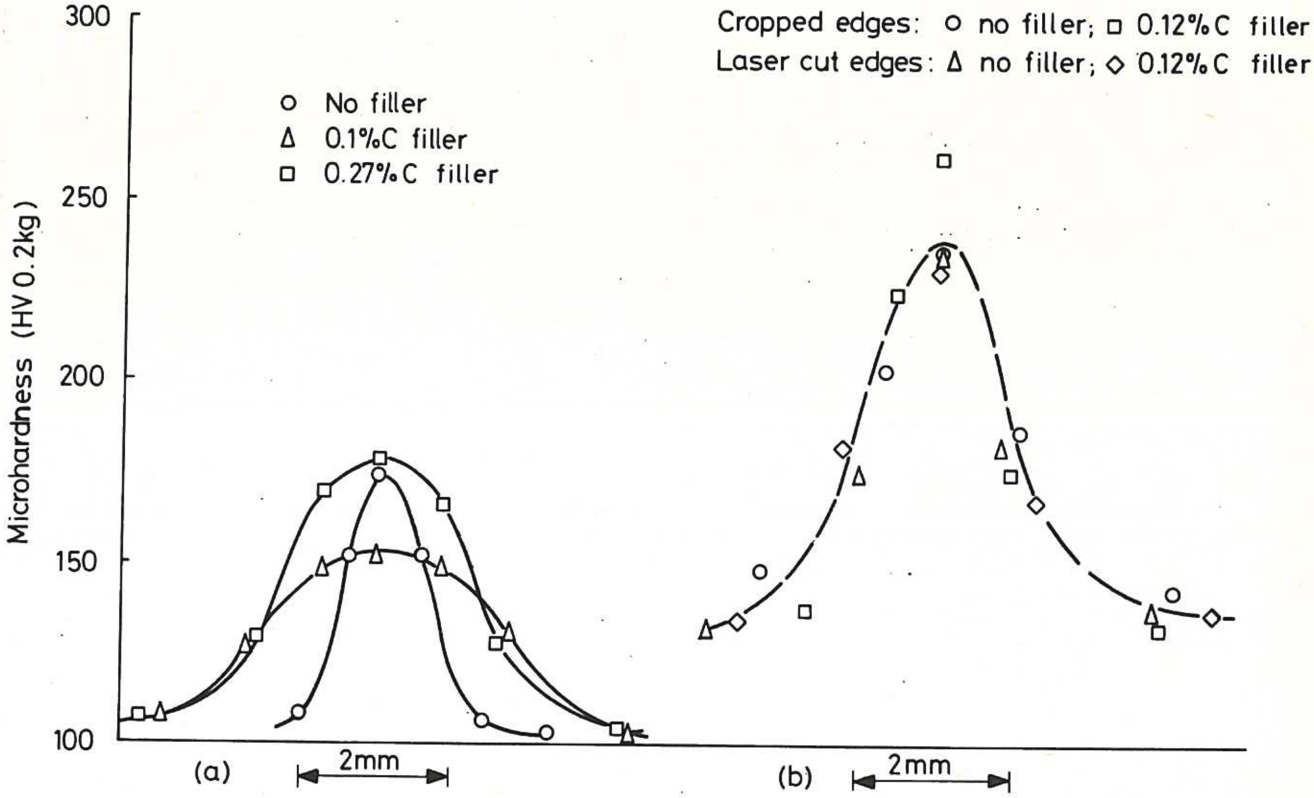

Fig 14. Hardness Scans Across Laser Welds in Mild Steel Plate
(a) Plate P1 (~0.06%C); (b) Plate P2 (~0.12%C).

CLM-P649