CLM - P702

CLM-P702

UKAEA

Preprint

LASER WELDING EXPERIMENTS
for the closure of irradiated fuel tranport containers from fast breeder reactors

J. H. P. C. MEGAW
M. HILL
J. BERNARD
M. MOULIN
J. VIVIEN
J. GEFFROY
J. P. NOEL

CULHAM LABORATORY
Abingdon Oxfordshire

1983

CLM-P 702

LASER WELDING EXPERIMENTS
for the
closure of irradiated fuel transport containers
from fast breeder reactors

by

J H P C Megaw*, M. Hill*, J. Bernard**, M. Moulin***,
J. Vivien***, J. Geffroy*** and J P Noel***

SUMMARY

Some of the irradiated materials from fast neutron reactors must be transported in flasks containing a cooling fluid (sodium). Hermetic sealing is performed by means of a plug forming a metal-to-metal seal, and then a cap is welded to the body of the flask. Welding characteristics are:

butt welding in the horizontal-vertical position;
flasks of 350 mm internal diameter;
stainless steel type AISI 316.

The laser welding process was thought to be worth developing because of the limited shrinkage and distortion of the welded parts and the small amount of space occupied in the active cell by the equipment.

A development programme was carried out on behalf of the CEA/DEMT by A.C.B. in collaboration with the UKAEA Culham Laboratory using the Laser Applications Group's 5 kW laser. Results of a three phase programme are presented in this report.

To be published in the proceedings of the 3rd International Colloquium on Welding and Melting by Electron and Laser Beams, Lyon, 5th–9th September 1983, organised by Commissariat à l'Énergie Atomique and l'Institut de Soudure.

July 1983

* Laser Applications Group, UKAEA Culham Laboratory, Oxon. OX14 3DB, UK.
** A.C.B., Nantes, France.
*** CEA–CEN, Saclay, 91191 Gif-sur-Yvette, France.

INTRODUCTION

For examination in active laboratories, some irradiated fuels from fast-neutron reactors have to be transported in flasks containing sodium to provide for their cooling. Hermetic sealing of these flasks can be effected by a plug forming a metal-to-metal seal to contain the sodium coolant, the complete end then being capped by a lid welded on to the body of the flask.

The process of autogeneous welding by high-power laser beam was considered worth developing because of the low shrinkage and distortion of the welded parts and the small space occupied in the active cell by the equipment.

A butt-weld is formed in the horizontal-vertical position, the flask axis being vertical. The joint has to be made between two pieces of type 316 stainless steel tube, of 350 mm internal diameter and 10 mm wall thickness.

A development programme for this welding process was carried out on behalf of CEA/DEMT by A.C.B., Nantes, in collaboration with the Laser Applications Group, UKAEA Culham Laboratory, and using their 5 kW laser CL5.

DESCRIPTION OF THE PROGRAMME

The programme was carried out in phases in order to investigate and optimise the process with regard to the following aspects: geometry of the joint; nature of the material; accuracy required; variation of thickness; alignment of the joint; weld closure and slope-out; weld speed; power; position of focal point; numerical aperture of the focusing system; and application to actual size mock-ups with simulation of the optical path (about 10 m with several reflections of angle).

The main phases were:-

Phase 1 The investigation and optimisation of welding parameters for flat samples.

Phase 2 The study and optimisation of effects resulting from: (i) variations in the joint geometry (misalignment, variation of relative thickness, form of joint, etc.); (ii) change over to circular geometry (using tubes of half final size, and with horizontal axis of rotation).

Phase 3 Establishment of the welding parameters needed for butt-welding actual size tubes in the horizontal-vertical position with simulation of the optical path (10 m).

EXPERIMENTAL EQUIPMENT

The CO_2 laser used for these tests was the transverse gas flow type CL5, developed at Culham Laboratory. Although it is industrially rated to operate at 5 kW, it can operate at over 6 kW for short periods. The discharge current and the gas flow are orthogonal, as shown in Figure 1. The laser has an unstable cavity, giving an annular beam of 42 mm outer diameter. Photo. 1 shows beam intensity patterns at 0·5 and 10 m from the output window. The cavity is folded into two parts and the cavity mirrors are mounted on an optical bench independently supported on air cushions; the output window is made of ZnSe.

Two CL5 lasers are in use, one at Culham and a second at the UKAEA Springfields Nuclear Laboratory, Preston. A 10 kW unit, CL10, consisting of two 5 kW modules, is also operating at Culham.

In Phases 1 and 2, the beam path length was ~ 4 m and it led via one mirror to a focus unit of the type shown in Figure 2A. In Phase 3, a beam path simulating the travel of the beam in the cell was constructed, as shown in Photo. 2. The path included 3 plane mirrors and because of diffraction effects filling the annulus, an off-axis focusing configuration (Figure 2B) was adopted.

Earlier work (1) showed that in welding, a significant focusing parameter is the depth of field ℓ which is related to the beam divergence θ such that:

$$\ell = \frac{2 f^2 \theta}{d_O}$$

where f = focal length

d_O = diameter of the laser beam at the mirror

i.e. the spot diameter can only be reduced to the detriment of the depth of field. During all the tests in the following 3 phases we used apertures of f/6 and f/8.

The focus position in relation to the workpiece surface was optimised to give maximum penetration and a parallel sided weld; this position lay slightly below the workpiece surface (1). Figure 3 gives the depth of penetration as a function of the welding speed for type 316 stainless steel with 5 kW at the work. It can be seen that as speed is decreased, there is a penetration limit. The significant parameter for maximum penetration is linked with the stability and density of the plasma formed in and above the "keyhole"; it is also linked with the beam intensity and the flow rate of the plasma control gas. In our tests the plasma was regulated by a jet of helium accurately directed to the interaction point. At low welding speeds regulation of the plasma became more difficult.

PROGRAMME PHASES

PHASE 1

Objectives

The objective of this stage was to determine the optimum welding parameters of the flat samples in order to obtain a weld of nuclear quality (Table 1):-

- Laser beam power
- Welding speed
- Position of focus
- Thickness of workpiece
- Geometry of the joint.

Results

In this stage, we made 100 welding tests.

For reasons of convenience, we allocated to the welds a quality factor (QF) which defined in a subjective manner the degree of porosity (as seen by radiography) on a scale from 1 to 10

(10 was free from porosity, 7 and above was considered to be satisfactory).

Table 2 shows the QF figures, together with the welding parameters obtained during the tests; this table also shows the macrographs of some of the welds.

Comments

Welding of the thickest section was easier and better when the power was increased.

For a given power, welding became easier and better when the thickness was reduced from 9·75 to 9 mm and then to 8 mm.

Porosity was lowest with an f/8 focusing mirror.

The results for a 9 mm thickness appeared to be best when using a bevelled edge at f/8.

For an 8 mm thickness, the weld was of high quality at f/6 with a welding speed of 14 mm s^{-1}.

Phase 2 was undertaken in accordance with the above observations and results obtained.

PHASE 2

Objectives

In this second phase of the tests, it was our aim:-

(a) To study, with flat samples:
- shrinkage;
- the influence of inadequate surface alignment;
- the influence of faulty beam alignment at the joint.

(b) To carry out some complete circular welds on samples with a diameter equal to half that of the flasks (168 mm), the axis of the tube being horizontal. The objective was also to study problems related to the overlap region (ramping down of the power) and the effect of the atmosphere behind the weld (N_2) on the quality of the joint.

Results

(a) Flat Samples

The effect of shrinkage: on 5 samples welded with 5 kW power, at a speed of 5 mm s^{-1}, we measured an average shrinkage of 0·5 mm.

Inadequate surface alignment: the results are shown in Figure 4. With square-edge preparation a tilting of the melted zone can be noted, which was due to a deflection of the helium jet (plasma control). This effect was less marked with a chamfered preparation because the bevel tended to centre the jet of gas; however it did present some difficulty.

Faulty alignment of the beam: with a 1 mm misalignment at each end of the bead, observation of the welding of the two ends shows complete fusion (Figure 5).

(b) Cylindrical Samples

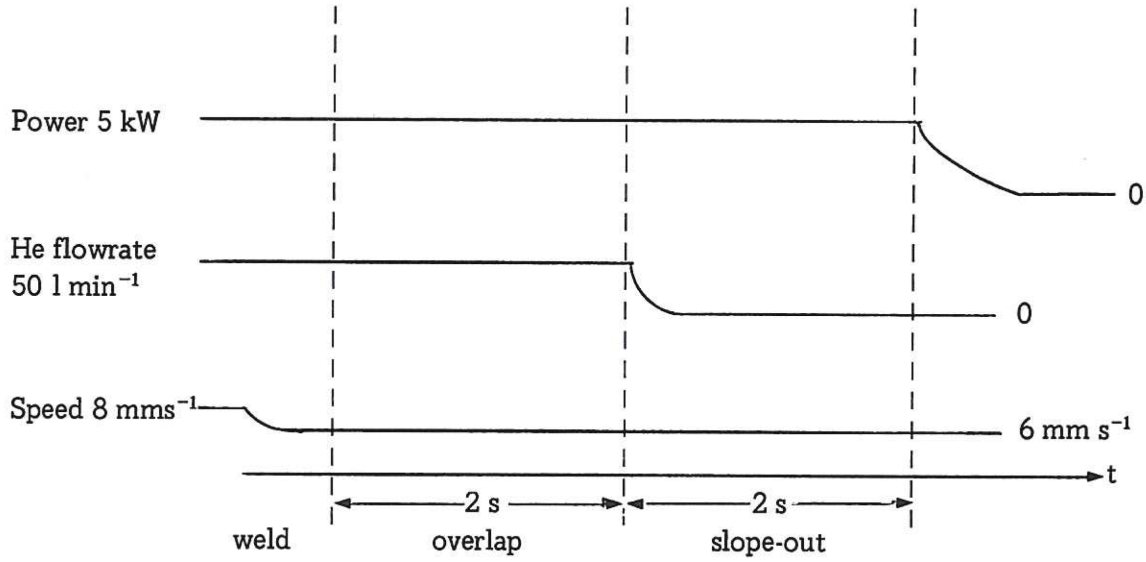
Here the work was particularly related to the overlap region with a horizontal axis of rotation. It was found that the pressure of the plasma control gas had a tendency to disrupt the melt pool and eject some molten material.

Some preliminary tests showed the need:

(i) to reduce the welding speed before the overlap;

(ii) to cut-off the plasma control gas after a 10 mm overlap, followed by the laser power slope-out.

We choose to operate according to the following diagram:



f/8 focusing was used in these tests. In Figure 6 we show the results obtained for two cylindrical samples. A dimensional check correlated the results obtained with flat samples and gave an average of 0·5 mm for shrinkage of the weld.

Comments

Knowledge acquired in this stage permitted optimisation of the welding parameters for a full size tube, the significant results obtained from this being:

- small shrinkage, of 0·5 mm;
- simple technique leading to good completion of the weld;
- simplified joint geometry (square butt);
- excellent reproducibility of the weld.

PHASE 3

Objectives

The objectives of this phase of the work were:-

1. To carry out welding operations remotely (10 m), simulating an optical path to the in-cell welding conditions.
2. To investigate the effects of a nitrogen atmosphere inside the tube (as in the actual cell).
3. To carry out welds on a tube with the actual dimensions of the flask cap, with nominal thickness 8·5 mm, and under conditions 1 and 2 above.

The experimental conditions of the simulated beam line are shown in Photo.2, and are described in the section entitled "Experimental Equipment". It must be noted that the optical components assembly of the beam line absorbs 13% of the energy.

A rotating device was constructed; it permitted displacement of the horizontal axis of the tube vis à vis the laser beam; a hermetically sealed lid was provided with an orifice for purging by nitrogen at slight overpressure (10 mm H_2O). Table 3 shows typical parameters of the weld.

Results

Out of 14 tubes welded, 6 were rejected for known causes (Table 4), and 8 were judged to be satisfactory. Figure 7 shows results regarding the sample (4 + 14). The effect of nitrogen purging was tested on 2 tubes. Figure 8 shows macro and micrographs of sections from sample (1 + 24): the nitrogen did not seem to have affected the quantity of ferrite. This result conforms to those obtained by arc welding with a nitrogen shield (2) (3).

Conclusion and Comments

The tests presented showed that it was possible to seal satisfactorily a nuclear fuel transport flask by laser welding under cell-working conditions; this did, however, require a 5 kW laser source (in this case the CL5).

It must be noted that these overall positive results were achieved within the scope of a programme of general evaluation of the feasibility of the laser welding procedure; this report cannot prejudge the reliability of the method, which can only be considered in a second stage of tests.

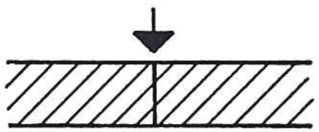
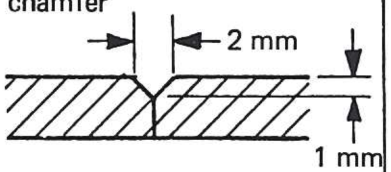
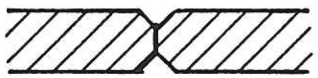
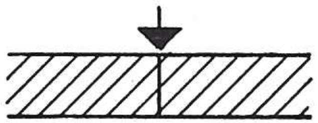
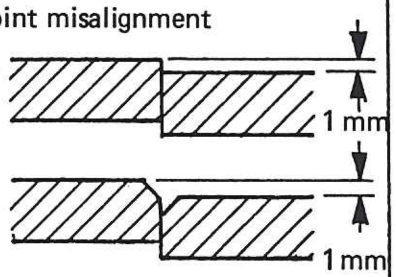
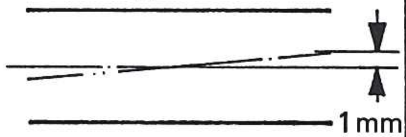
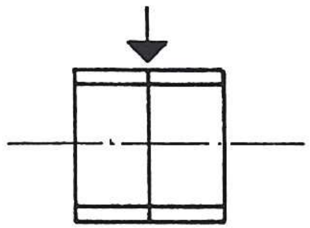
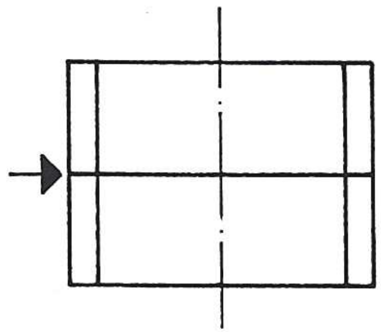
REFERENCES

(1) "Assessing the laser for power plant welding", R.A. Willgoss, J.H.P.C. Megaw, J.N. Clark, Welding and Metal Fabrication, March 1979, pp.117, 127.

(2) "Purging with nitrogen in the welding of austenitic stainless steels", C.V. Shirwaikar and G.P. Reddy, Welding Journal, January 1975, Res. Suppl., pp.12-s, 15-s.

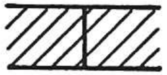
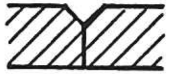
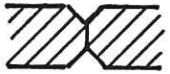
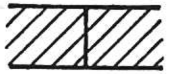
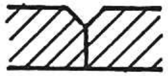
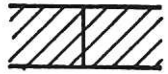
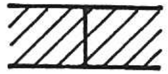
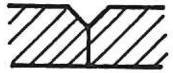
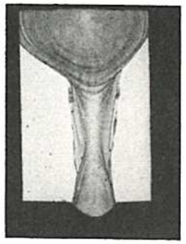
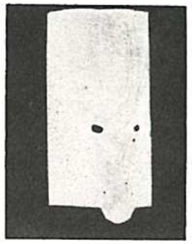
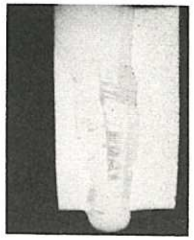
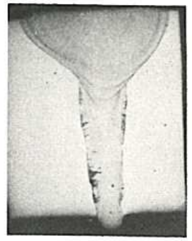
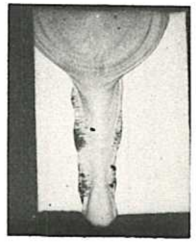
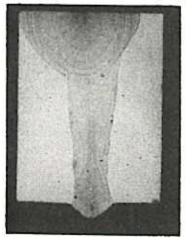
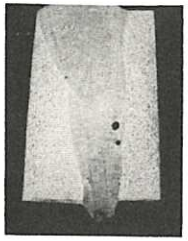
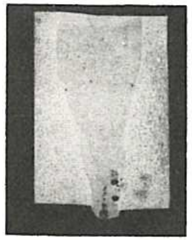
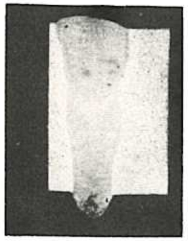
(3) "The nitrogen contents of Fe–Cr, Fe–Ni and Fe–Cr–Ni weld metals", T. Kobayashi, T. Kuwana and Y. Kikuchi, Transactions of J.W.S., April 1970, pp. 35, 42.

Table 1. Type and geometry of the samples.

Material: Stainless steel type AISI 316			
Phase 1	**Phase 2**		**Phase 3**
Geometry: Flat plate		**Cylindrical Tube**	
Square-butt preparation  45° chamfer  Double chamfer 	Study of shrinkage  Joint misalignment  Beam misalignment 	Horizontal axis Square-butt 	Vertical axis Square-butt 
Dimensions: Length 100 mm Width 2 x 18 mm Thickness 8, 9 & 9·75 mm	Dimensions: Length 100 mm Width 2 x 18 mm Thickness 9·75 mm	Dimensions: Diameter 168 mm Length ~ 2 X 90mm Thickness 9 mm	Dimensions: Diameter 348 mm Height 2 X 185mm Thickness 8·5 mm

CLM-P702

Table 2. Phase 1 results and allotted quality factors.

Thickness	Laser/Workpiece Power: 5·5/5 kW					6·5/6 kW		
	f/8			f/6		f/6	f/8	
								
9·75 mm		8 	6 	5 	5 	7 	8 	10 
9 mm	10 	9 	9 	6 	8 			
8 mm	10 	9 		9 				

CLM-P702

Table 3. Process parameters.

Beam power at laser	5·3 kW
at work	4·6 kW
Sample diameter	349 mm
thickness	8·5 mm
Mirror focusing, nominal	f/8
Off axis, total angle	9°
Mirror focal length	~ 335 mm
Focus position set empirically by maximising penetration.	
Estimated tolerance on focus position with respect to work.	± 5 mm approx.
Welding speed, main weld	8 mm s^{-1}
overlapping	5·7 mm s^{-1}
Ramp-out by switching off plasma control gas followed ~ 2 seconds later by switching off beam.	
Plasma control gas flow (helium)	~ 55 l min^{-1}
Estimated tolerance on this	± 5 l min^{-1}
Additional shroud flow (helium) (probably capable of being reduced)	~ 400 l min^{-1}
Estimated positional tolerance of plasma jet	
with respect to workpiece surface	⩽ ± 0·5 mm
with respect to beam centre line	⩽ ± 0·5 mm
Estimated positional tolerance of beam centre line with respect to joint	⩽ ± 0·5 mm
Acceptable surface mis-match "step"	⩽ 0·5 mm

Table 4. Comments on 14 tests on full size tubes.

ACB SAMPLE NUMBERS	TRIAL 1	TRIAL 2	TRIAL 3
1 + 24	Totally misaligned	Incorrect focus	N_2 Satisfactory
16 + 22	Faulty plasma control	Incorrect focus	Satisfactory
17 + 19	Satisfactory	Satisfactory	
18 + 12	Misaligned	N_2 Laser tripped off. Restarted Satisfactory	
20 + 23	Satisfactory		
6 + 21	Plasma control incorrect	Satisfactory	
4 + 14	Satisfactory		

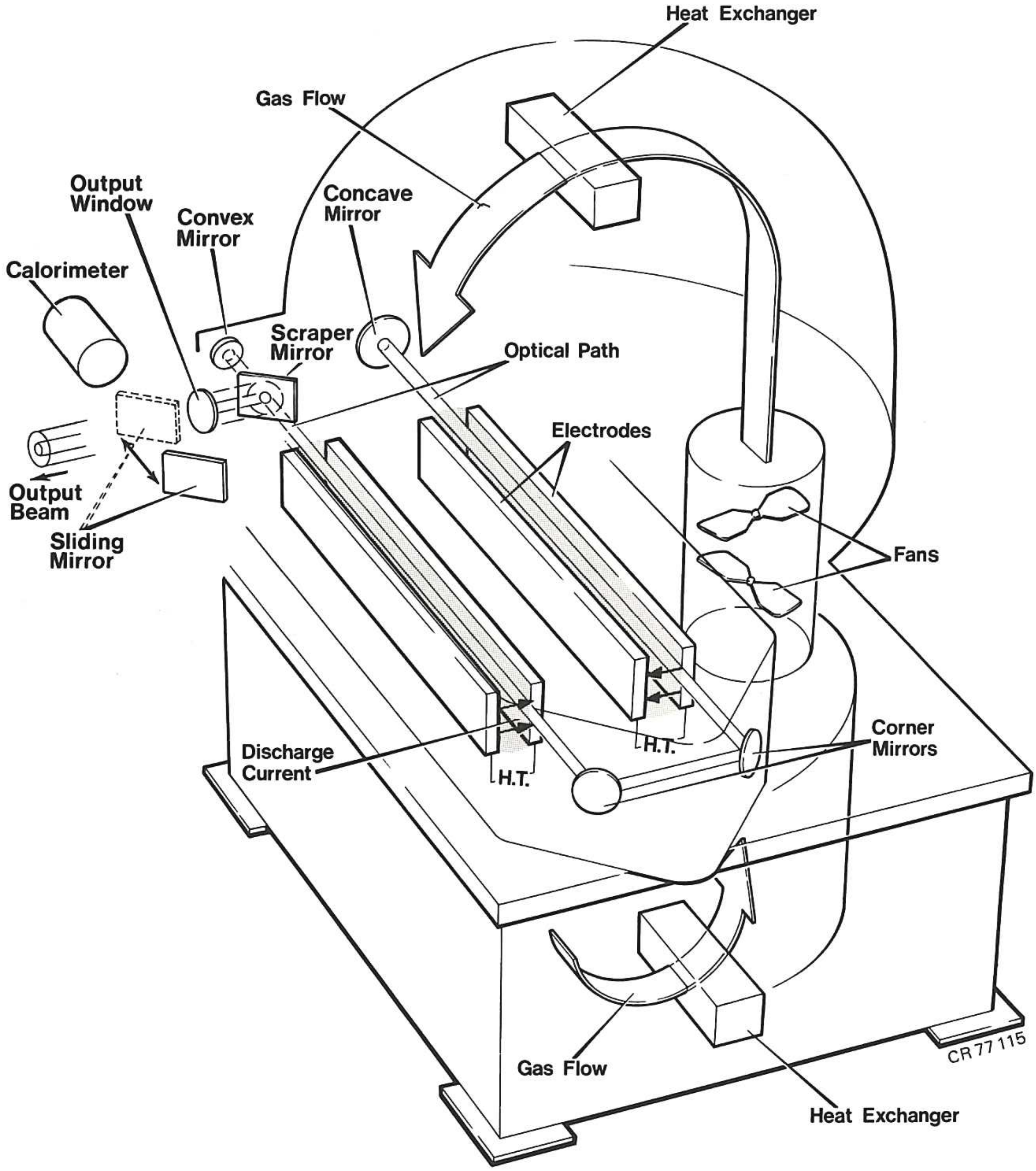


Fig. 1 Schematic of the CL5 laser.

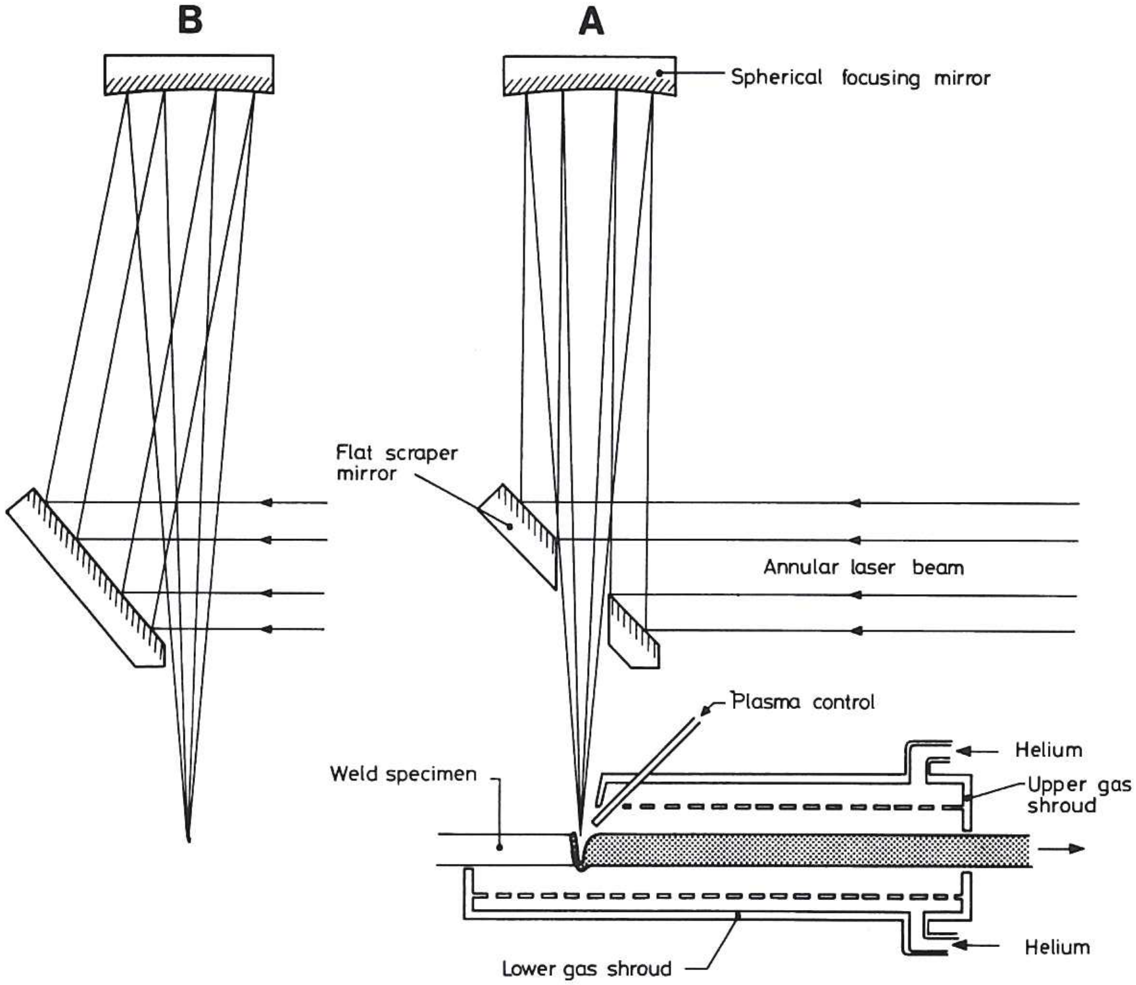


Fig.2 Focusing the gas jet arrangement.

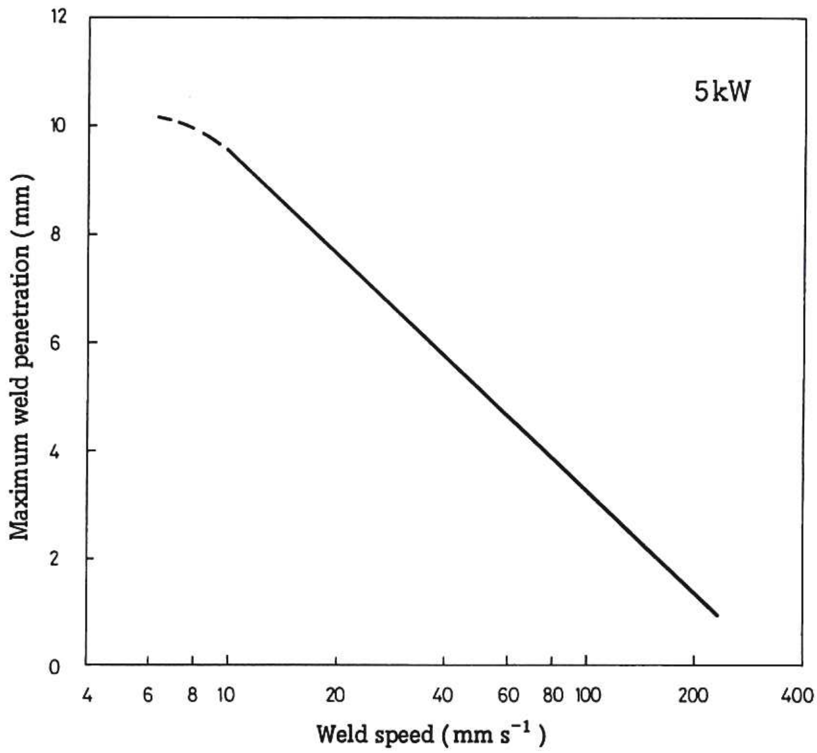
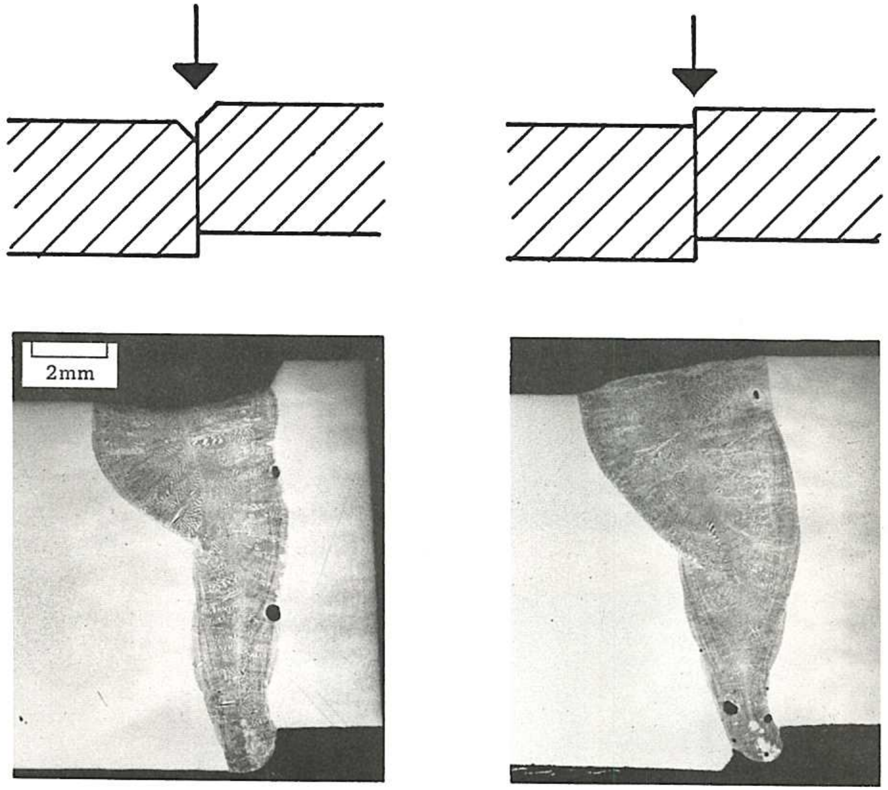


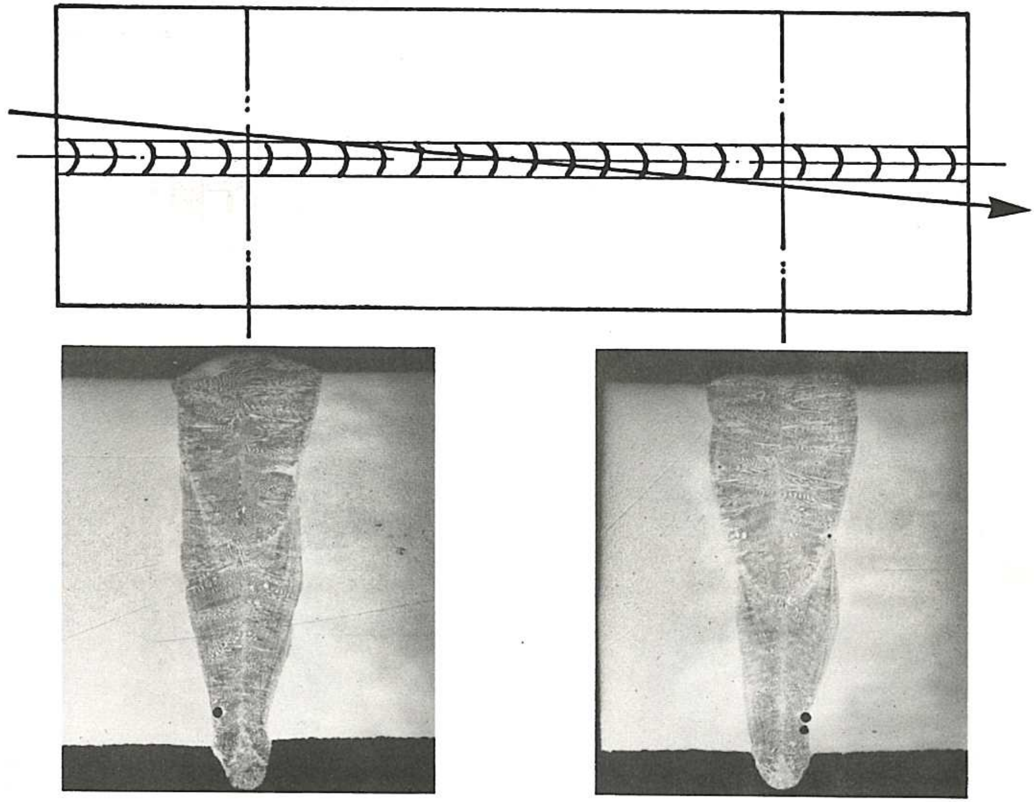
Fig.3 Guide to penetration as a function of welding speed.



5·5kW
10mm s^{-1}
f/6

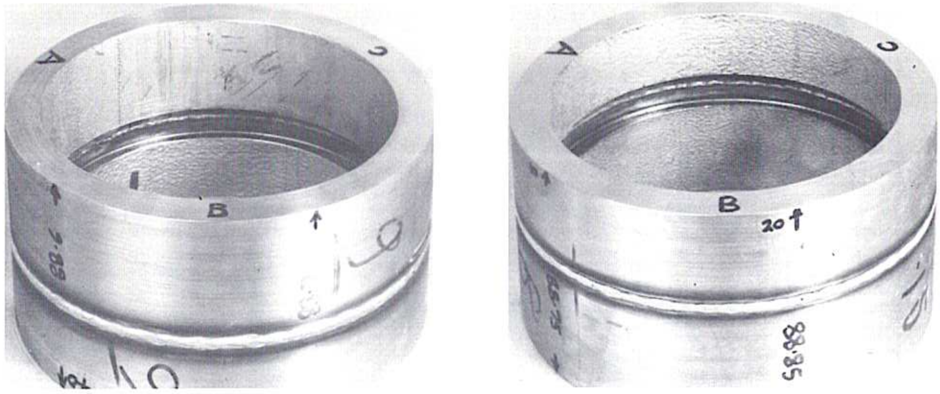
5·5kW
8mm s^{-1}
f/6

Fig.4 Effects of joint misalignment in 9mm plate.



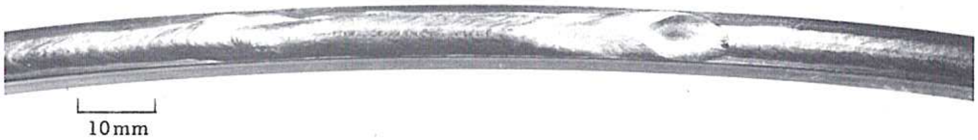
5·5kW
8mm s^{-1}
f/6

Fig.5 Effects of beam misalignment in 9mm plate.

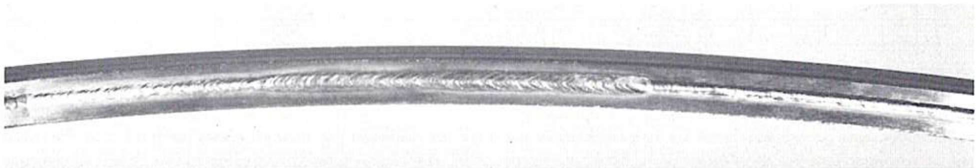


9mm thickness, 2mm chamfer　　　　8mm thickness, Square-butt

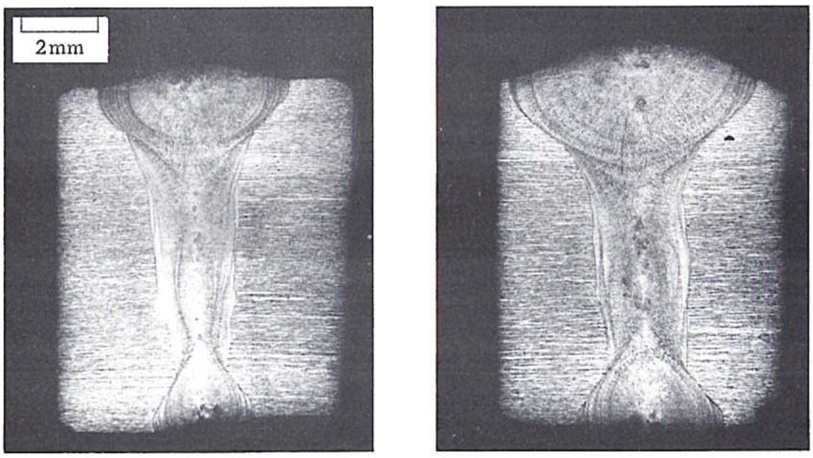
Fig. 6 Appearance of welds in 168mm diameter tube.



Overlap—outer bead

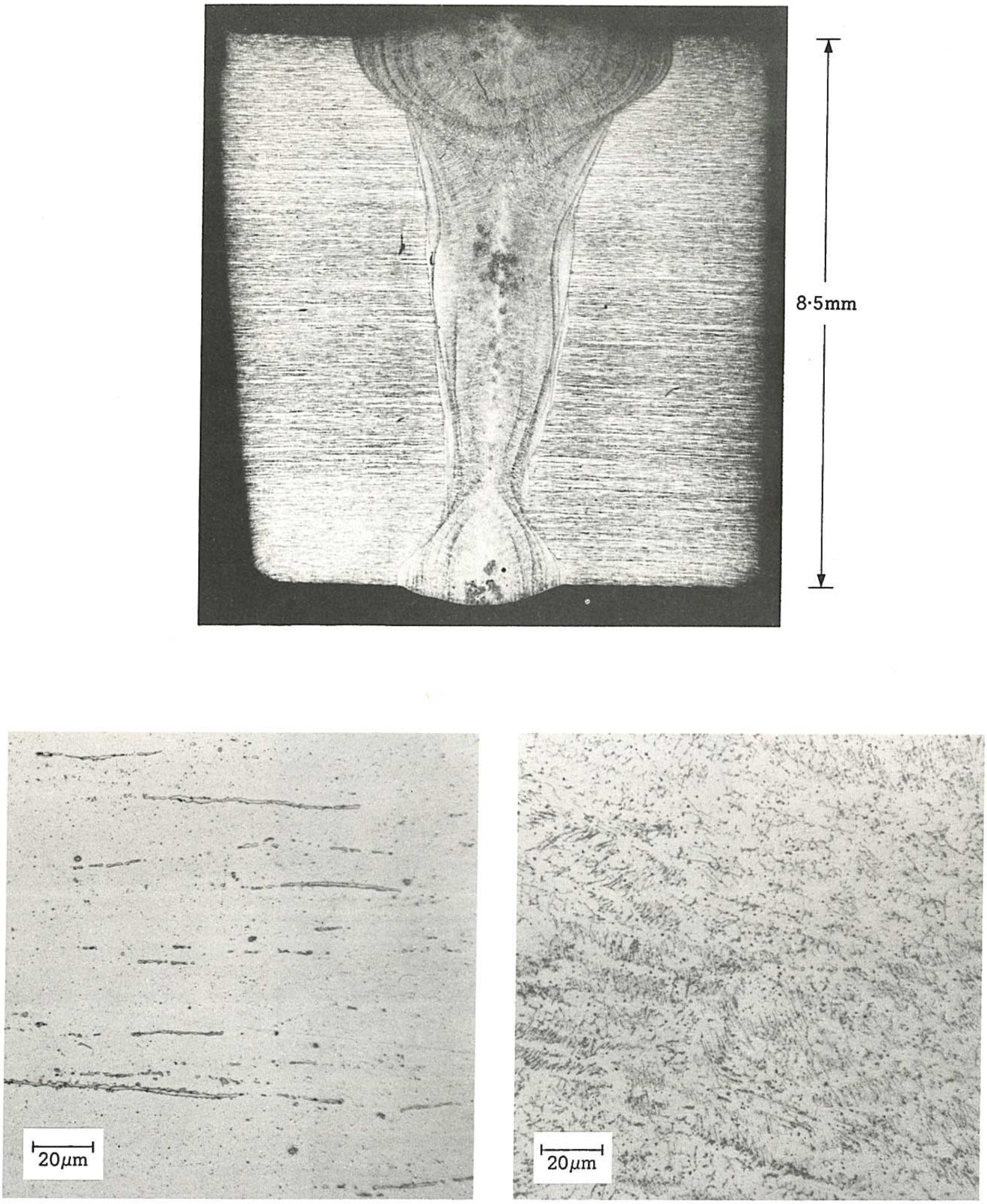


Overlap—inner bead



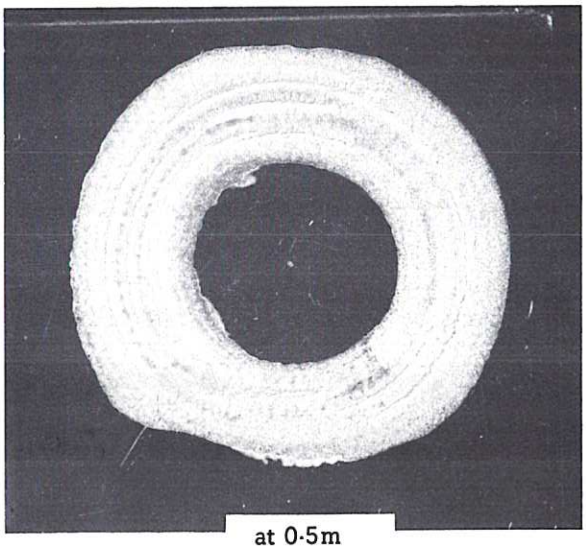
Weld　　　　Overlap

Fig. 7 Results of welding a full size tube of thickness 8·5mm.

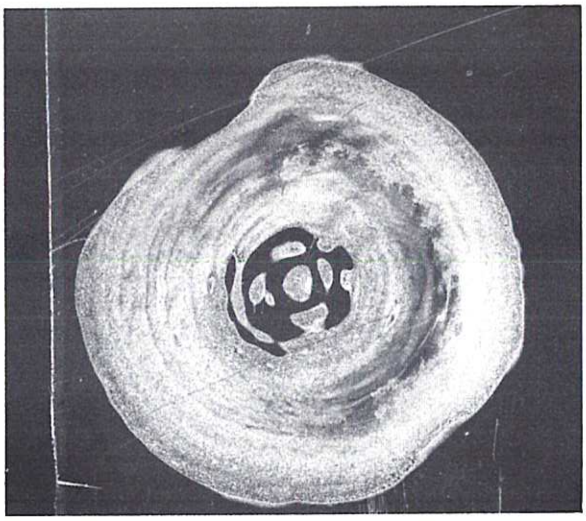


Parent Weld

Fig.8 Effects of nitrogen inner shield.



at 0·5m



at 10m

Photo. 1 Beam intensity prints in acrylic.

CLM-P702

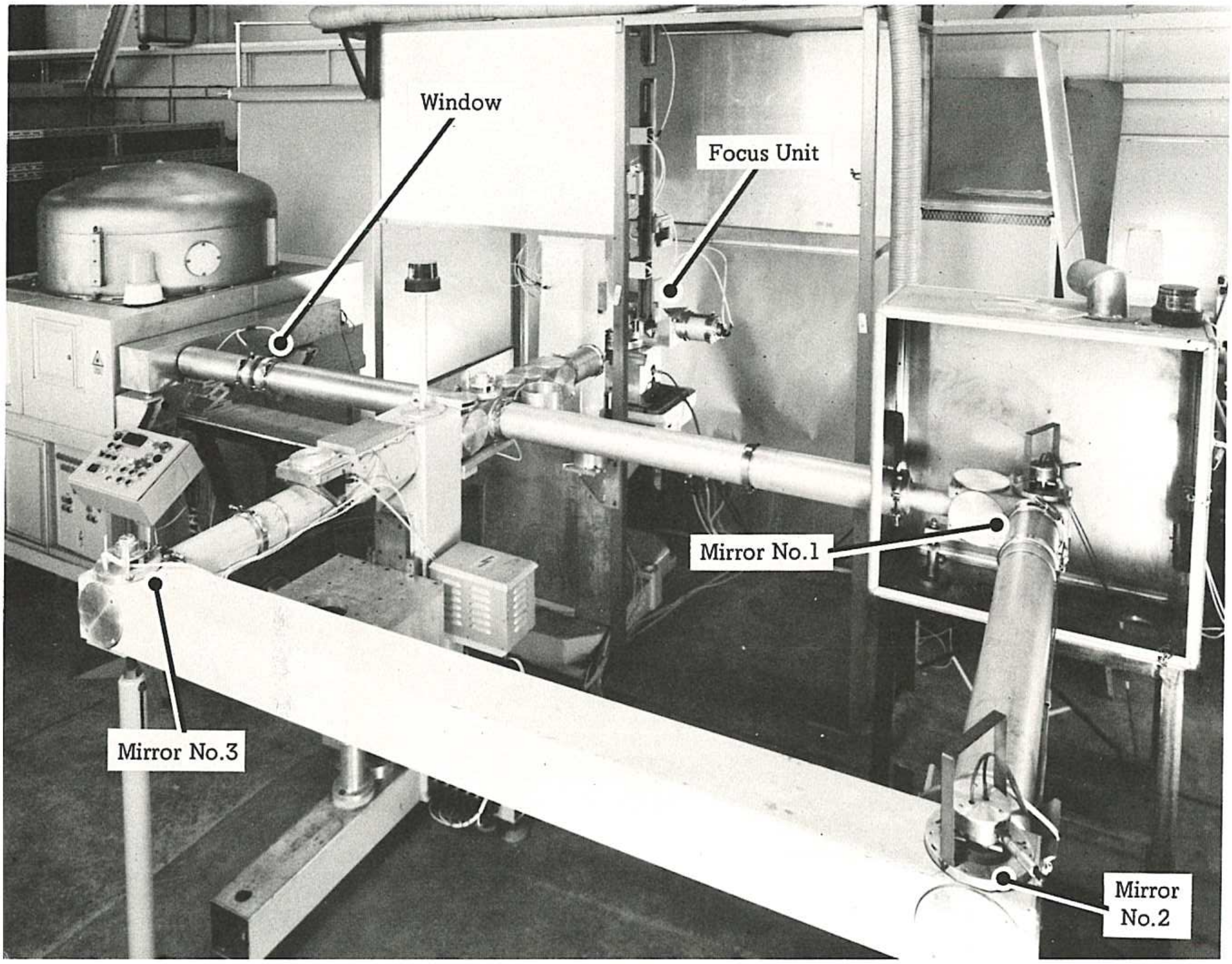


Photo. 2 Beam line layout.

CLM-P702

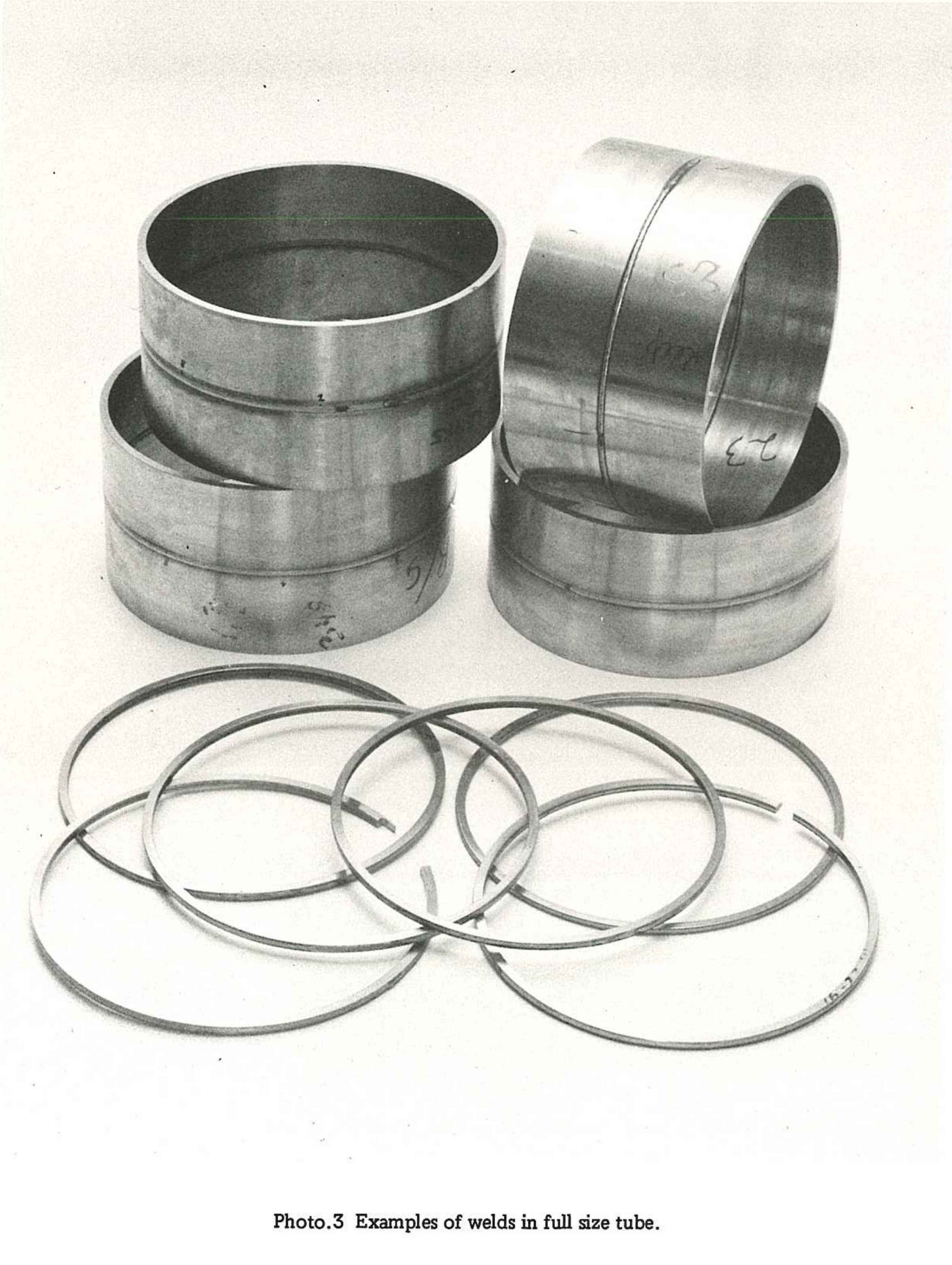


Photo.3 Examples of welds in full size tube.