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SUMMARY

This paper describes an investigation of 10kW CO₂ laser welding undertaken during BRITE Project 1206, where a major objective was to demonstrate automatic welding of large steel components with commercial edge preparations. A brief description of the overall project and some of the features of a 6m-stroke welding gantry are presented, together with a detailed account of the moving welding head equipment. The experimental procedure, where several different fillers were added to single-pass welds in 12mm thick Type Q1N steel plate, is described. Results of macro and micro-examinations, hardness measurements and Charpy impact tests show that welds with encouraging properties were produced.

INTRODUCTION

A three year European research and development project, BRITE P1206 - Adaptive Control of Laser Processing (1), on industrial applications of high power lasers for cutting, welding and surface treatment of metals was completed successfully in September 1989. A partnership of over twenty organisations, ranging from small and medium sized enterprises to large multi-nationals, from the Netherlands, West Germany and the United Kingdom sponsored the Project. Companies from a variety of industries, including several involved in shipbuilding and off-shore activities, were represented. Whilst the TNO Applied-Physics and Metals Institutes in the Netherlands used 300W Nd:YAG and 1.2kW CO₂ lasers to develop techniques for cutting, hardening, micro-machining (2) and surface texturing of metals utilised in the production of moulds for manufacturing plastic components, the Laser Technology Centre at Culham Laboratory studied the application of multikilowatt CO₂ lasers. A major objective was to design and construct a large-scale gantry to demonstrate adaptive control of welding with a 10kW CO₂ laser. Ultimately, the goal was the implementation of an automatic welding process on a moving welding system capable of operating continuously and over long distances. That necessitated studying various aspects of laser welding, in particular those affecting the welding process in thick-section steels, e.g. welding high strength materials and multi-pass welding. For some of the investigations a high yield strength quenched and tempered steel, Type Q1N, which is of particular interest in warship construction, was chosen in 12 and 25mm thicknesses. A further objective was to develop laser welding techniques suitable for use with commercial plate preparation, i.e. consistent with either readily machinable edge profiles or, if possible, flame cut edges.

Early developments at Culham using a 5kW CO₂ laser to weld guillotined and laser cut edges in 6mm mild steel plate with the addition of filler wire were very encouraging (3) and the potential for exploiting this technique in shipbuilding has been described (4). Similarly, the potential for joining heavier sections, such as off-shore pipeline, with a 10kW CO₂ laser using a moving welding head has also been demonstrated (5). Therefore, development of a fully automated laser welding process, with adaptive control of height following, seam tracking and joint gap filling, appeared to be a logical next step when formulating this BRITE project. Although the project was conducted

on a confidential basis, it is possible to report here some of the less commercially sensitive aspects and an account of the investigation into single-pass welding of 12mm thick Type Q1N steel plate with filler wire addition is presented.

EQUIPMENT

Welded specimens were produced with the 10kW CO₂ laser CL10 on the BRITE P1206 6m-stroke welding gantry, shown in Fig. 1. Figure 2 shows schematically the 12-18m flight path, where the beam (6) is transmitted via seven plane mirrors through a height changer and servo alignment mechanism to the welding head which contains a further two plane mirrors and an off-axis aspheric $-f/12.5$ focusing mirror, as shown in Fig. 3. The complete welding head is mounted on a vertical slideway and transported on the gantry carriage. Figure 4 shows the travelling 10kW CO₂ laser welding head producing a bead-on-plate melt run in 12mm mild steel during open-loop trials. Much of the optical system was designed, tested and assembled during the first two years of the project (7).

Welding was performed in the downhand attitude in pairs of plates held horizontally and clamped together on a table designed to carry test specimens up to 6m long. Plasma control and protection against oxidation of the top surface was provided by means of a Culham standard gas shield (3), within which a 2mm diameter jet of inert gas is directed at an angle of 45° 1mm ahead of the laser beam/workpiece interaction point (Fig. 3). Filler wire, fed from an NEI/TWI Whiz-step wire feeder, was directed at -60° to the plate surface to a position ~2mm ahead of the interaction point through three guide rollers. This auxiliary wire-feed mechanism, also developed during the project (7), proved very effective in straightening the wire and stabilising its pointing direction. Although not utilised for the work reported here, the welding head incorporated an Oldelft Seampilot vision system capable of sensing the transverse position, height and size of the joint gap and of providing feedback control to the motors which determine weld head position and wire feed rate.

MATERIALS

Type Q1N plate was supplied and prepared for the laser gantry welding trials by VSEL. Specimens ~300mm long by ~150mm wide were flame cut from 12mm thick plates; some of the specimens were machined along one edge either normal to the plate surface to provide a square-butt fit-up or at 5° from normal to give a 2mm wide V-preparation between pairs of close butted plates. The latter preparation was chosen to maintain sufficiently wide gaps to accept ~1mm diameter wires and to allow adequate penetration of filler materials throughout the plate thickness. All of the plates were descaled by sand blasting, oiled to prevent rusting during storage and then cleaned with Genklene before welding. An average of chemical analyses from four plate samples is given in Table 1.

Five different types of welding wire were used. Initial trials were made with a double de-oxidised MIG welding wire, DIN8559-SG2, originally specified for a shipbuilding application and used successfully in the second year of this project for double-pass welding in 25mm material (1). Another double and a triple de-oxidised wire to BS2201, Part 1-A18 and A15 respectively, were employed: A18, because it is more readily available than SG2; A15 for possible use with flame cut edges. Linde 95 wire was chosen because it is used in arc welding Q1N plate to give high strength and toughness. Since flux cored wires have shown considerable improvements in laser weld metal microstructures and Charpy impact energies at low temperature (8) (9), a wire of this type, Dual Shield II-101TM was also tried. The L95 and DSII were supplied by VSEL and specimens from all five wires were arc melted under argon shielding and chemically analysed by VSEL, with the results shown in Table 1.

Table 1 Chemical analyses of plate and fillers (%Wt)

Element	Average Q1N Plate	Filler				
		SG2	A18	A15	L95	DSII
C	0.14	0.06	0.04	0.035	0.07	0.05
Mn	0.29	1.35	1.29	1.07	1.68	1.10
P	0.012	0.015	0.015	0.013	0.008	0.006
S	<0.002	0.012	0.017	0.005	0.006	-
Si	0.25	0.68	0.78	0.55	0.33	0.33
Ni	2.88	0.074	0.09	0.055	1.66	1.66
Cr	1.35	0.014	0.06	<0.01	0.1	0.02
Mo	0.37	0.01	0.006	0.015	0.31	0.01
Ti	0.006	0.005	0.004	0.080	0.01	-
V	0.007	0.006	0.006	0.009	<0.01	0.02
Cu	0.016	0.53	0.27	0.20	0.02	0.01
Co	0.011	0.007	0.013	0.013	-	-
As	0.007	0.004	-	-	-	-
Sb	<0.005	<0.005	-	-	-	-
Pb	<0.002	<0.003	-	-	-	-
Sn	0.002	0.004	-	-	-	-
Al	0.026	<0.002	<0.005	0.045	0.02	-

EXPERIMENTAL PROCEDURE

During the first two years of the project a wide ranging parametric study on keyhole phenomena was made using off-line radiography and on-line, real time radiography. The study showed that fully penetrating welds, with low levels of porosity, could be produced in 12mm mild steel with a power ~8kW at the work and welding speed ~10mm/s, when focusing the CL10 beam with off-axis spherical mirrors between f/8 and f/16. Therefore for the gantry welding trials a 500mm focal length mirror, equivalent to ~f/12.5, was used with a power of 7.5 ± 0.2kW at the work. Initially, a series of bead-on-plate melt runs were made and the focus position was chosen to be 2mm below the top surface of the plate, for which condition maximum penetration was obtained for a given power and speed. Helium was used throughout for plasma control and shielding; jet, lens and top shroud flow rates were 15, 50 and 50 l/min respectively. Those were the optimum values found for the bead-on-plate runs and they also proved to be very effective when welding with filler.

An investigation was then performed to find suitable combinations of welding speeds (S) and filler wire feed rates (R) to fill the 2mm Vee joint gap. As a starting point the ratio of wire feed to welding speed was assumed to be equal to the ratio of joint gap area (A) to wire cross-sectional area (a). Thus:

$$\frac{R}{S} = \frac{A}{a} = \frac{0.5wt}{\pi r^2}$$

where (w) is the Vee top width, (t) plate thickness and (r) wire radius. Allowing for shrinkage (δ) and angular 'butterfly' distortion (α) during welding, A is reduced so that:

$$\frac{R}{S} \approx \frac{(0.5w - \delta - 0.5t \tan \alpha)t}{\pi r^2}$$

Therefore, for $t=12\text{mm}$, $w=2\text{mm}$, $r=0.5\text{mm}$ and assuming $\delta \sim 0.25\text{mm}$ and $\alpha \sim 1^\circ$ (as measured in previous CL10 welding with filler): $R/S \approx 9.9$. In practice, when welding with the 1.0mm diameter SG2 wire a fully penetrating weld was produced with good joint gap filling by using a welding speed of 8mmms^{-1} and wire feed rate of 80mmms^{-1} . Therefore, 1.0mm diameter A15 and A18 wires were used with the same speeds and produced similar results. A feed rate of 95mmms^{-1} for 0.95mm diameter L95 wire produced a good result at the same welding speed, giving $R/S \approx 12$ compared to the 10.9 calculated. For 1.2mm O.D. DSII wire, weld and wire speeds of 8mmms^{-1} and 80mmms^{-1} respectively gave an acceptable result.

Two attempts were made to feed 1.0mm diameter A15 wire at 50 and 25mmms^{-1} into joints between flame cut plates with an 8mmms^{-1} welding speed. Both attempts failed due to the wire not entering the narrow joint ($<1\text{mm}$ wide) and deflecting out of the molten region, thus producing two autogenous welds. Two further autogenous welds were produced at 6 and 12mmms^{-1} in close butted joints with machined edges for metallurgical comparison of welding with high and low heat input, i.e. nominally 1.25 and 0.63kJmm^{-1} respectively.

RESULTS

Visual examination of the underside of the welded plates showed full penetration and generous under beads in all welds except for the high speed (12mmms^{-1}) autogenous weld which had only partial penetration. Top beads were smooth and indicated adequate filling in most welds. Those welded with A18 and DSII fillers were slightly under-filled. The autogenous welds in flame cut edges were also under-filled, with slightly disrupted top beads. Photomacrographs of sections from each of the welds are shown in Fig. 5. Satisfactory weld bead profiles and good side-wall fusion are seen for all of the welds with filler, but the autogenous welds are rather barrel shaped and therefore not ideal. Micro-porosity near the fusion boundary is seen only in the welds with A18, A15 and L95 fillers.

Hardness measurements were made with a Vickers diamond point hardness tester using a 10kg load at various positions across the weld beads and in the heat affected zones (HAZ) and parent plate on either side of the welds. Tests were made at three positions within the plate thickness, i.e. 1.5mm from the top and bottom surfaces and at the plate centre. Average on-axis weld hardnesses range as follows: SG2, 373HV_{10} ; DSII, 379HV_{10} ; A15, 385HV_{10} ; 12mmms^{-1} autogenous 391HV_{10} ; 6mmms^{-1} autogenous, 392HV_{10} ; A18, 395HV_{10} ; L95, 404HV_{10} ; flame cut edges, 408HV_{10} . Hardness varies across the HAZ: in the lightly etched regions close to the fusion boundary (see Fig. 5) hardnesses are comparable with, or sometimes a little higher than those on the weld axis, with a maximum value of 425HV_{10} near the top of the HAZ of the L95 filler weld; in the outer HAZ regions typical values are generally below 300HV_{10} , whilst the average parent plate hardness is 223HV_{10} . These values should be noted in the context of VSEL's maximum acceptance value of 350HV_{10} .

Charpy impact toughness tests were made in $10\text{mm} \times 10\text{mm}$ specimens machined from each welded plate, with the V-notch running from top to bottom of the weld bead and its centre placed on the weld axis, i.e. running vertically in the sections shown in Fig. 5. Tests were made at temperature intervals of 10°C from 0°C to -70°C for each weld. The measured impact energies where specimens broke along the weld centre line are plotted in Fig. 6; values usually $>200\text{J}$, where the fracture deviated into the parent plate, were ignored. The graphs show that two of the filler wires, SG2 and DSII, produced average Charpy values greater than the VSEL average acceptance value of 85J at -50°C . The values for double and triple de-oxidised wires (A18 and A15) were slightly below that requirement, although they were higher than the minimum acceptance value of 50J . Results for L95 were considerably lower than expected, surprisingly so since this wire gives excellent impact properties ($80\text{--}95\text{J}$ at -50°C) with conventional arc welding.

Autogenous welding of machined edges appears to be fairly satisfactory, giving almost exactly the required average Charpy value. However, the flame cut edges when welded without filler gave less than half that value, presumably reflecting effects due to heavily oxidised edges.

Optical microscopy shows that generally the weld metal microstructures consist of coarse columnar untempered martensite near the weld crown, becoming slightly more equiaxed with weld depth. No acicular ferrite was observed, although the sub-grain microstructure of the DSII filler weld metal is considerably finer than any of the other welds. This is shown in Fig.7 in comparison with the SG2 filler weld metal. Close to the fusion boundary, the heat affected zone consists of coarse equiaxed grains of untempered martensite; this structure becomes increasingly tempered and fine grained as the fully-tempered martensite of the parent plate is approached.

CONCLUSIONS

Following completion of the design, construction and commissioning of the 6m gantry during the first two years of the project, it was possible to demonstrate successfully single-pass welding of 12mm thick Type Q1N steel plate by means of a moving 10kW CO₂ laser welding head and with the addition of various filler wires. Choice of a 2mm wide V-preparation enabled full-depth penetration of the filler materials, which produced sound weld bead profiles having good side-wall fusion, minimal slumping and smooth top and bottom beads. Small amounts of microporosity were seen in only a few of the welds. Weld shrinkage and butterfly distortion were low ($\sim 0.25\text{mm}$ and $\sim 1^\circ$) and consistent, thus allowing wire feed rates to be predicted accurately.

Addition of a particular double-deoxidised MIG welding wire, DIN8559-SG2, and a rutile flux cored wire, Dualshield II, produced low temperature Charpy impact energies satisfying the appropriate welding acceptance values for this material. However use of the TiO₂-containing flux-cored wire did not produce acicular ferrite as had been observed in previous laser welding of a pressure vessel steel (9). Charpy results for welds made with another double and a triple de-oxidised wire, A18 and A15, approached the average acceptance value, but those produced with a filler suitable for arc welding Q1N plate, Linde 95, were below that value. The autogenous welding of heavily oxidised flame cut edges resulted in greatly reduced impact energy, but the autogenous welding of machined edges at 6mmms^{-1} gave impact values comparable to some obtained in filler welding. Testing of the lower heat input (12mmms^{-1}) autogenous welds yielded more fracture deviation. It is also noted that there appears to be some correlation between the impact properties shown in Fig. 6 and the weld hardness noted above, i.e. the better Charpy performance of the SG2 and DSII fillers corresponds to weld hardness $<380\text{HV}_{10}$, whilst the poorer impact properties of the welds using L95 filler or flame cut edges correspond to weld hardness $>400\text{HV}_{10}$.

An attempt has been made to compare the present results with those from other work (10) on the autogenous laser welding of two casts of Q1N plate. Simple comparisons are rendered difficult by the ubiquitous problem of crack deviation, but it may be inferred that the present autogenous results indicate higher impact energies. This is difficult to explain on the basis of carbon content because it is here comparable with that of the preferred cast in the other work; on the other hand, sulphur levels in the present work are lower ($<0.002\%$ cf 0.003%).

In summary, notwithstanding the rather high hardness of the joint region in the as-welded condition, the measured impact properties are generally better than might be expected, given the growing body of data which suggests that laser weld toughness is an area requiring special attention.

ACKNOWLEDGEMENTS

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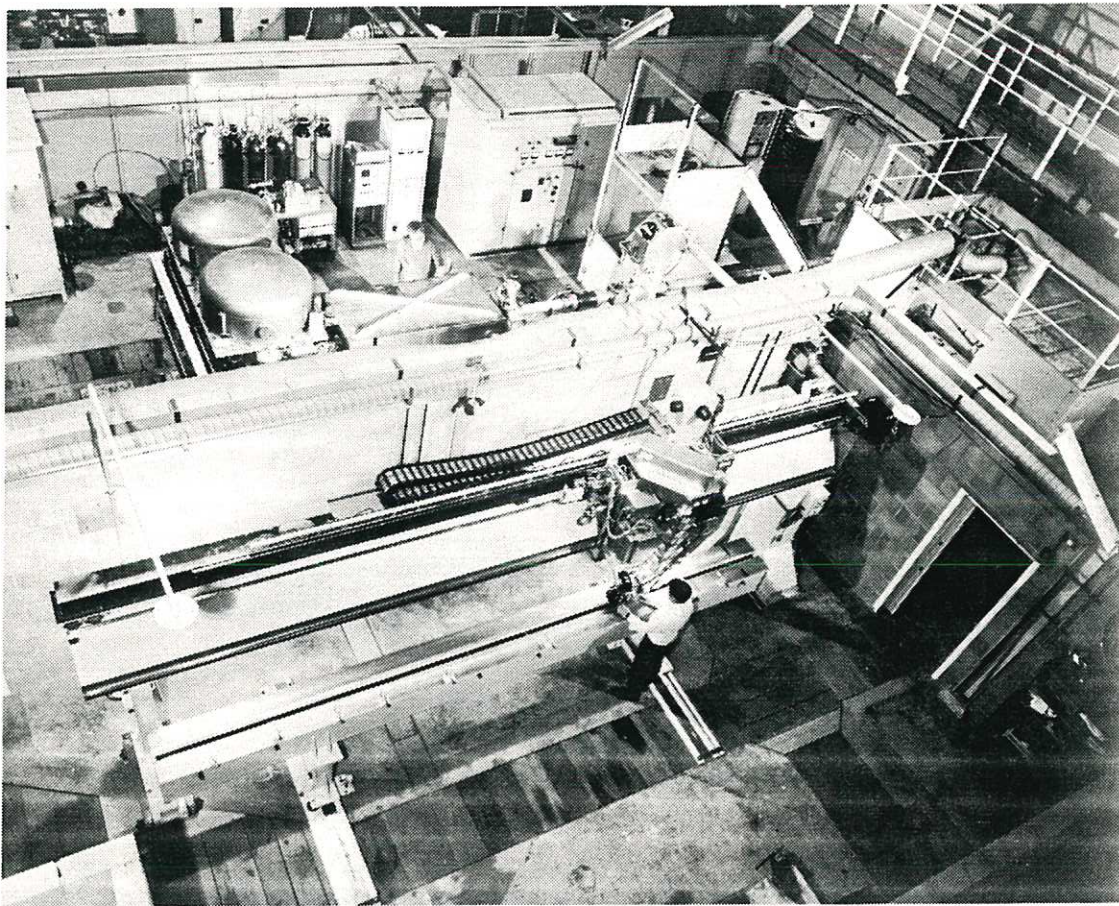


Figure 1. Overhead view of the 10kW CO₂ laser and the 6m welding gantry.

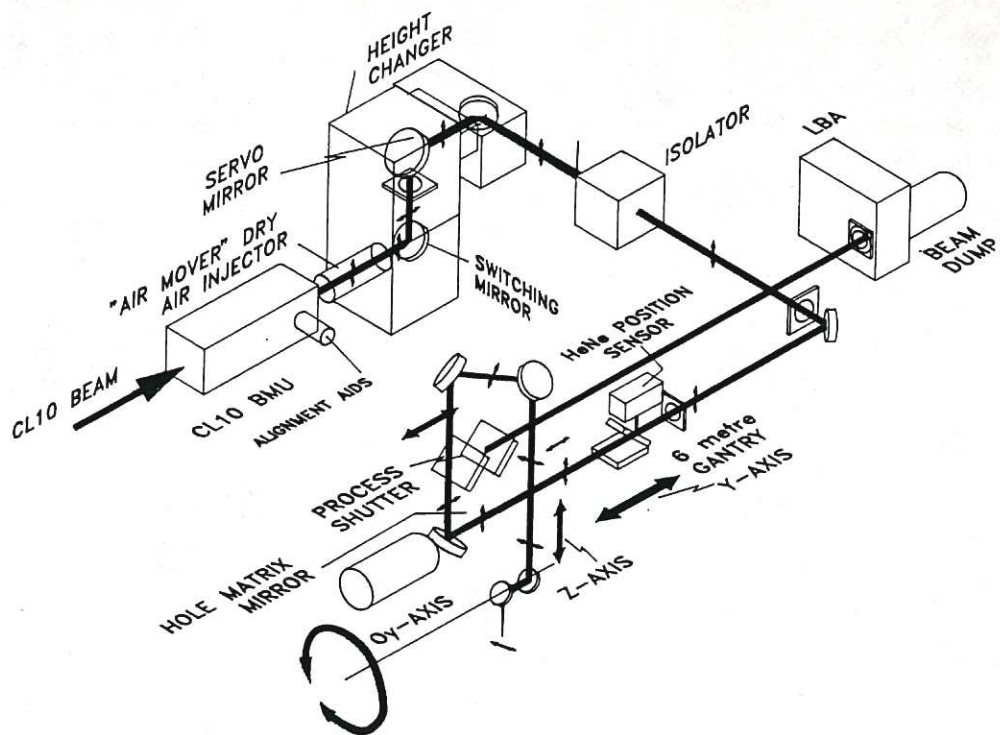


Figure 2. Optical schematic of the gantry system.

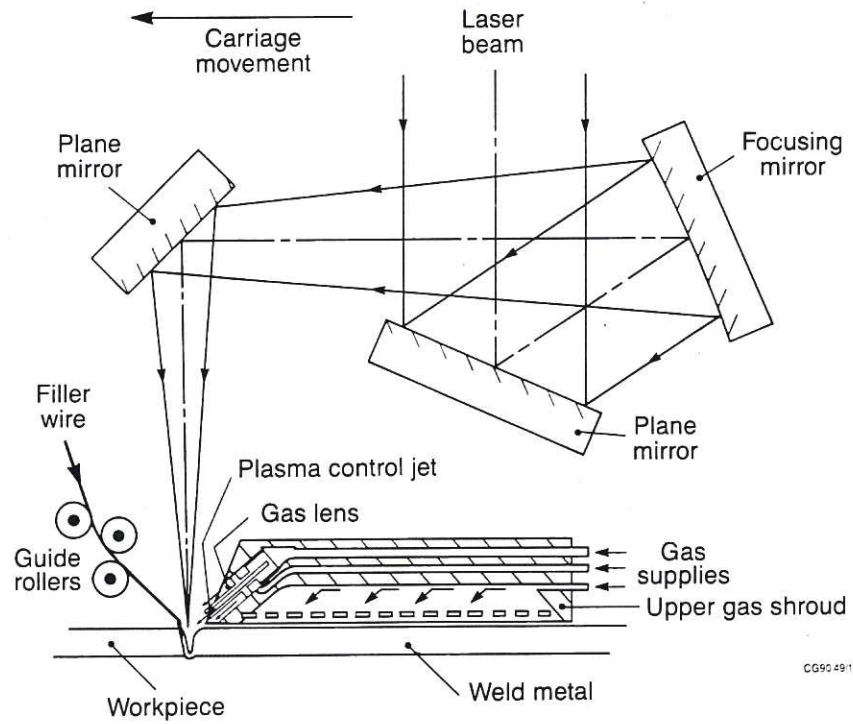


Figure 3. Laser welding head and wire feed schematic.

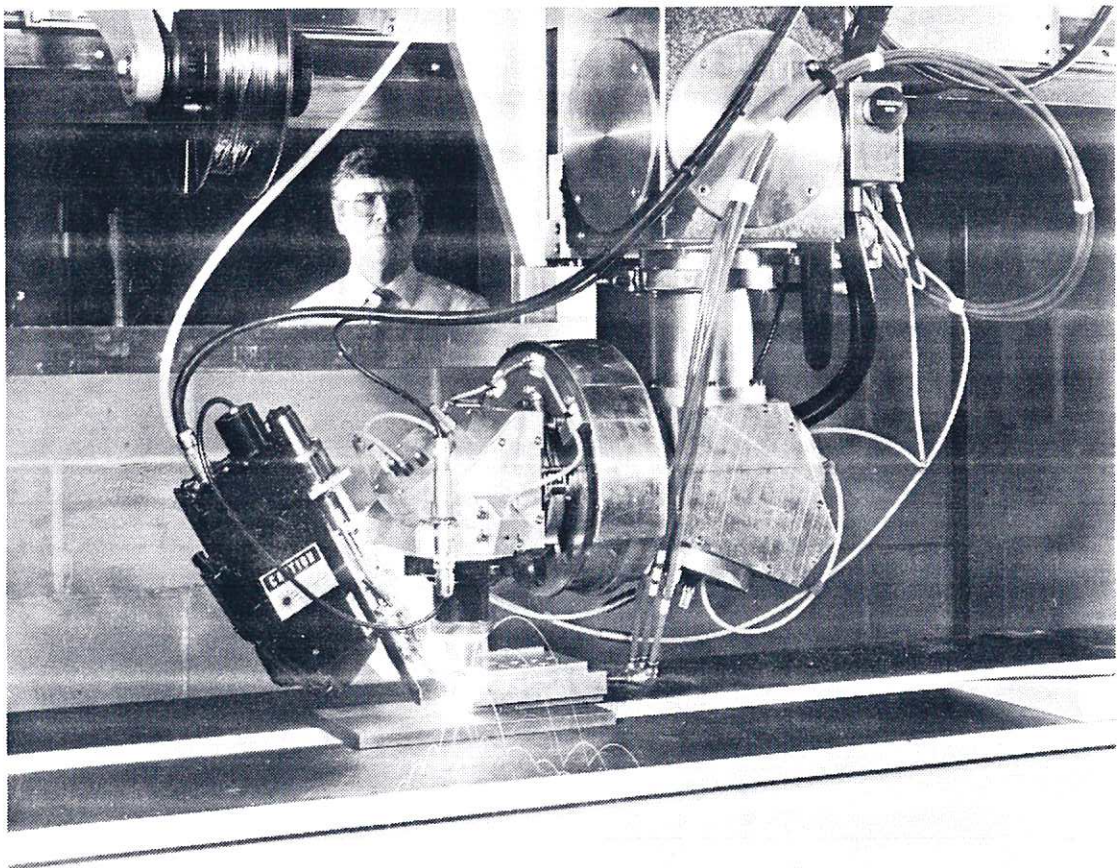
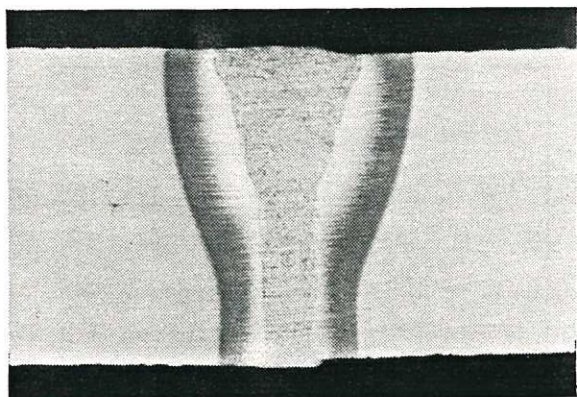
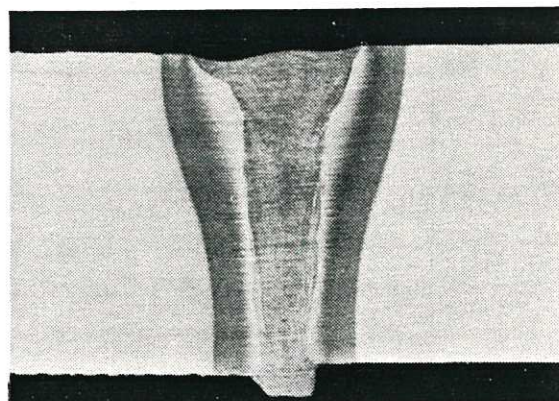


Figure 4. View of the laser welding head making a bead-on-plate run in 12mm mild steel on the 6m gantry.



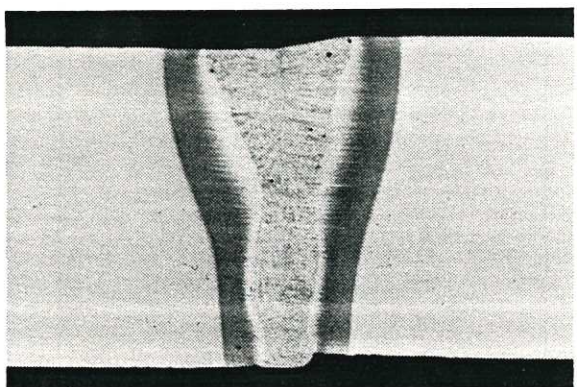
SG2 Wire

8mm^s⁻¹



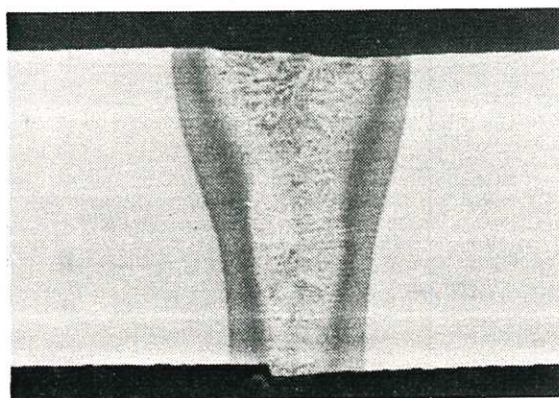
Dualshield II Wire

8mm^s⁻¹



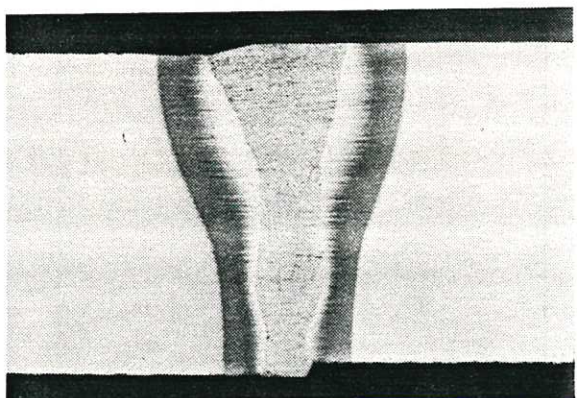
Al8 Wire

8mm^s⁻¹



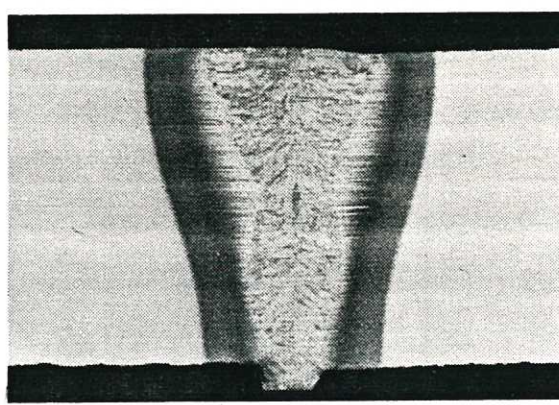
Flame Cut

8mm^s⁻¹



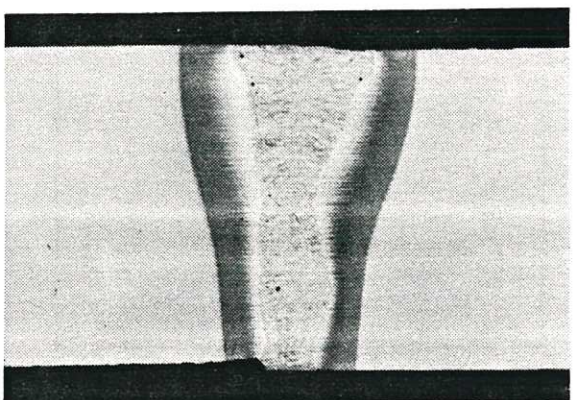
Al5 Wire

8mm^s⁻¹



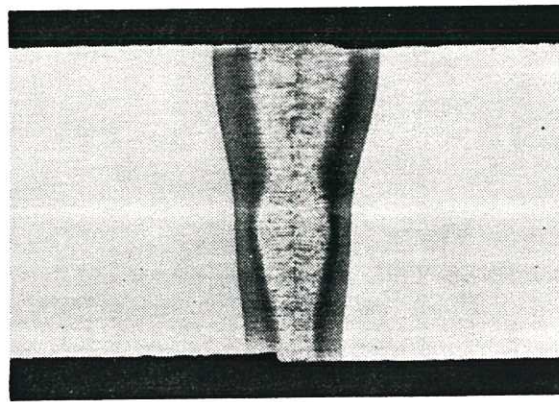
Autogenous

6mm^s⁻¹



Linde 95 Wire

8mm^s⁻¹



Autogenous

12mm^s⁻¹

Figure 5. Macro-sections from laser welds in 12mm thick Type Q1N steel plate.

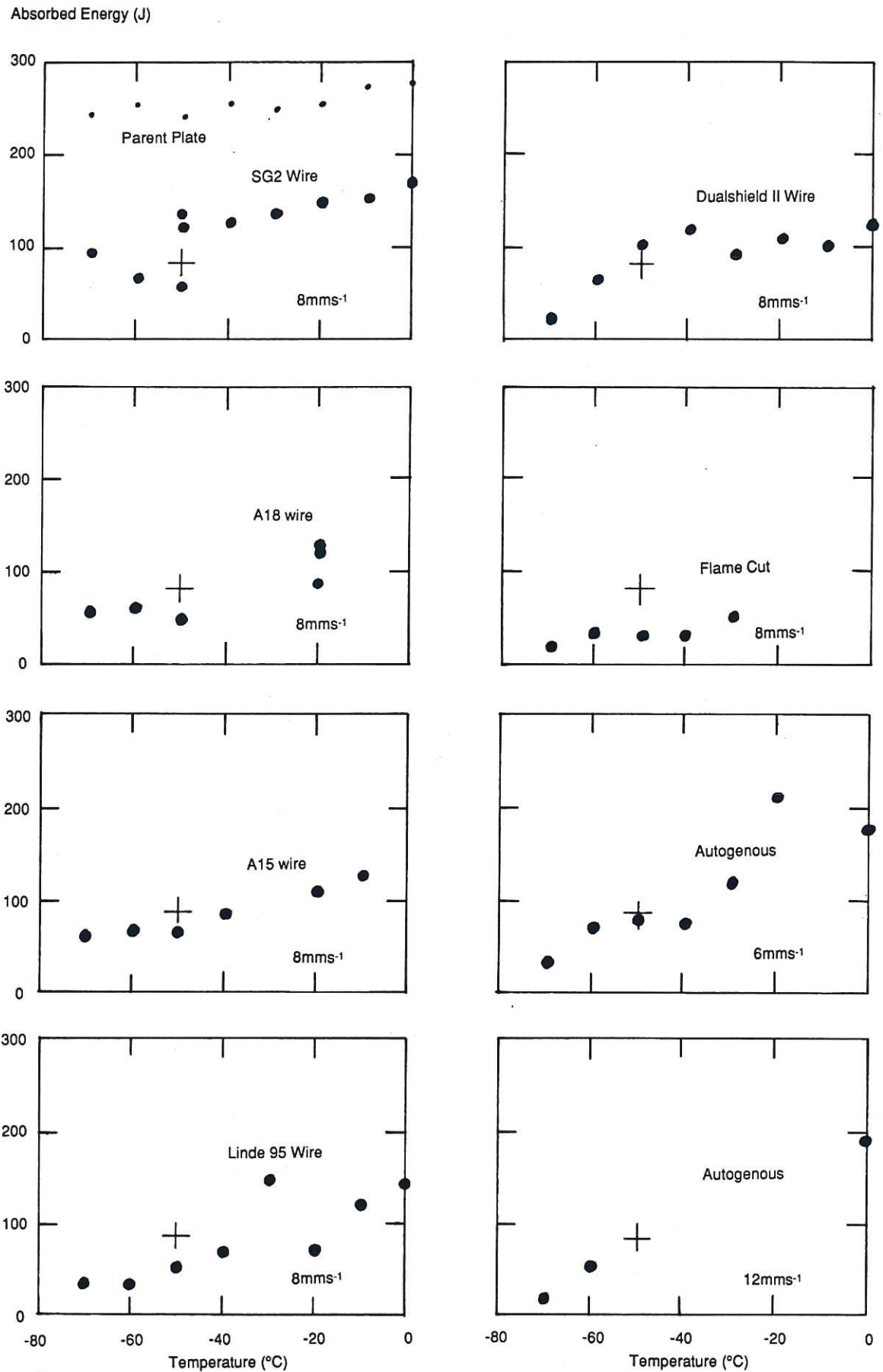
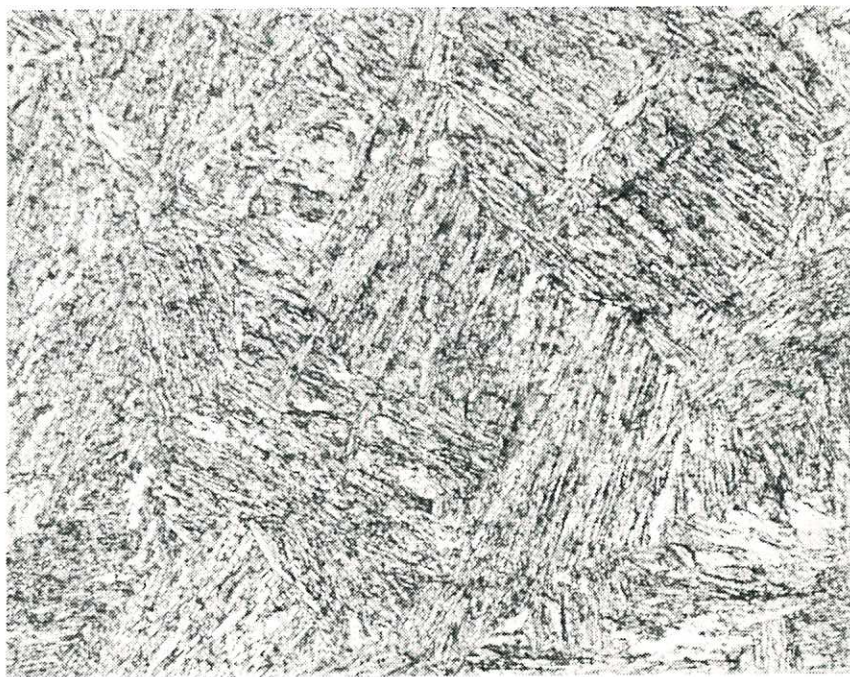


Figure 6. Charpy absorbed energies in laser welded Type Q1N plate: 7.5kW at work; + denotes VSEL average acceptance value.



20 μ m

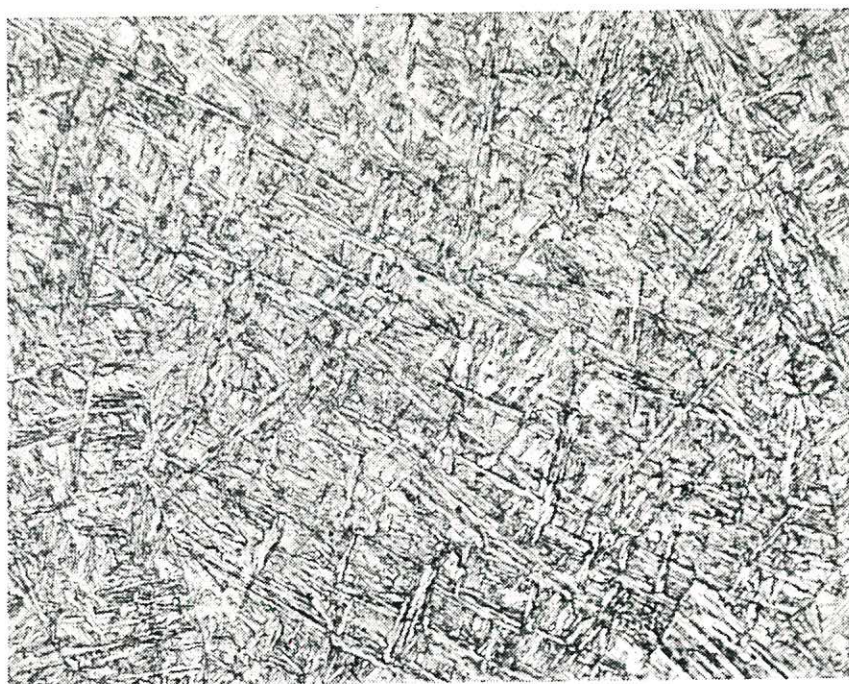


Figure 7. Weld metal microstructures from SG2 (upper) and DSII (lower) filler welds.

