The use of Power Beam Welding Technology in Manufacturing Industry

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Abstract

In order for manufacturing companies to remain competitive it is necessary for them to review continually their fabrication methods. The use of power beams for welding and cutting offer significant opportunities for industry to improve its product quality and increase profitability. This paper discusses a number of current industrial applications for electron beam and laser welding.

Introduction

Successful manufacturing operations rely on the appropriate application of technology to achieve the most efficient and cost effective production. Therefore, it is necessary for companies to review continually their manufacturing methods so that the fabrication and assembly of products are carried out using the most appropriate processes. Welding is usually an extremely important part of the manufacturing operation and thus developments in the technology of joining can significantly impact on its profitability.

Power beam welding has developed over the last 30 to 40 years and currently the range of industrial sectors that can benefit from the technique is expanding. Two types of lasers are currently being applied to welding, the CO_2 and the Nd:YAG laser. Electron beam welding can be achieved using equipment in vacuum conditions and developments are demonstrating the processes viability in on-vacuum and reduced pressure electron beam welding. This paper discusses all of these types of power beam process variants and identifies a number of current areas of industrial application for each one.

2. Characteristics and advantages of power beam welding

Power beam welding differs from all other joining techniques in many respects. It utilises a high energy beam of either photons, for laser welding, or electrons in the case of electron beam welding. The beam is projected into the joint which generally consists of closely butting parts with a square edge preparation and, ideally, no gap. The energy of the beam is sufficient to vaporise the material. Molten material, ahead of the vapour, is depressed and a keyhole is formed in the material. The depth of the keyhole is determined by the power employed and speed the of traverse. As the beam is moved along the seam, the liquid walled cavity solidifies behind the beam causing the joint edges to be welded. The resultant weld is characterised by parallel sided deep narrow fusion zone. Figure 1 shows a comparison of EB and submerged arc multipass welding for 100mm plate thickness in CMN steel. Power beams offer a number of advantages over conventional welding techniques including deep penetration single pass weld, high joining rate and travel speed, low and predicable distortion allowing welding of finished machined components, narrow weld and heat affected zone, simple edge preparation, no consumables, generally no pre-heat required.

3. Lasers

This offers many design and production opportunities not provided by conventional welding methods.

Laser Types

Two types of laser are currently used in industrial production for welding applications, $C0_2$ and the Nd:YAG laser.

$C0_2$ Lasers

The $C0_2$ laser uses a gas mixture confined within a glass tube optical cavity as a lasing medium The mixture comprises helium, nitrogen and carbon dioxide in the approximate ratio of 80:15:5. Helium is required as a heat sink to facilitate heat removal, while nitrogen acts as an initiator. $C0_2$ lasers produce a beam in the far infra-red with a wavelength of 10.6um. This wavelength is too long to be transmitted by glass optics or byoptical fibres, so mirrors (Au plated Cu, Si or Mo) and special lenses (made of KCl and ZnSe) are used for beam manipulation and focusing.

For welding applications in automotive manufacturing, $C0_2$ lasers with powers above 1kW are generally required where lasers are termed 'fast axial flow' and 'cross flow' which describes the way in which the gas mixture is handled by the machine for cooling purposes. The lasers mainly operate in a continuous wave mode.

Nd:YAG lasers

The lasing medium is a solid crystal of yttrium aluminium garnet doped with neodymium. The crystal is externally excited by high intensity flash lamps and produces a near infra-red beam with a wavelength of 1.06um. This wavelength can be transmitted through air and conventional glass optics and, more significantly, it can also be passed through optical fibres. Before, 1988, commercially available Nd:YAG lasers were restricted to a maximum average power of 500W but recent developments have led to the introduction of Nd:YAG lasers with average powers of 1-2kW and further advances are being made to develop Nd:YAG lasers with powers of 3-5kW. The lasers can operate in a continuous wave mode or with enhanced pulsing capabilities.

Other lasers

In addition to $C0_2$ and Nd:YAG lasers, other laser types are being developed which operate at different wavelengths. The major laser types and their characteristics are shown in Table 2, where information on excimer, carbon monoxide and iodine lasers is presented. At present, although there are developments to uprate the power capabilities of these lasers, their impact on welding in the automotive industry is likely to be limited for several years.

Cost of laser equipment

Typical capital costs of industrial $C0_2$ and Nd:YAG lasers are presented in Table 3. These figures are only indications and prices will vary according to supplier. The price does not include any work handling equipment. The Table shows that the cost of 5kW CO_2 laser is equivalent to the cost of a 2kW Nd:YAG laser at around £150,000.

Beam handling systems

The choice of laser will depend on the ultimate application where two dimensional or three dimensional processing may be required. For two dimensional processing, beam handling systems are simpler as a moving workpiece is normally involved. In this case, the choice of laser will depend on an assessment of production requirements and capital cost where CO_2 lasers are generally more economically attractive at present. For three dimensional processing, there is a greater dependence on the beam handling system and a comparison of the attributes of CO_2 and Nd:YAG lasers and their respective beam handling systems is presented in Table 4. From these factors, it can be seen that the use of Nd:YAG lasers with robotic manipulation of the fibre-optic cable is attractive for three dimensional laser processing providing the production rates are satisfactory.

Running costs/consumables

The running costs and consumables will depend on the laser type, power requirement and the component to be welded. An example of an analysis of the running costs and consumables for CO_2 and Nd:YAG lasers in a three dimensional welding application is presented in Table 5. This analysis has been taken further to produce information on hourly rates and piece costs (at full capacity) which is shown in Table 6.

The results of this analysis highlight the point that the economic considerations for choosing a laser for a particular welding operation are complex and the outcome will depend on all aspects of the manufacturing considerations.

We will now consider the capabilities and applications of CO_2 and Nd:YAG lasers separately.

CO_2 laser welding

Industrial CO_2 lasers are now available up to 25kW power with high power lasers in development (>40kW). At 10kW power single pass welding can be achieved up to 15mm in thickness of speeds of up to 1m/minute. Thin sheets in steels are commonly welded at 5kW power and at speeds of up to 10m/minute.

One of the primary advantages of the CO_2 laser is the ease with which it can be manipulated. The laser beam in an unfocused condition can travel many tens of metres with minimal loss of energy. Thus it can be delivered to the workpiece from the power source by a series of mirrors. The laser can be switched between multiple work stations offering significant potential for time sharing resulting in increased productivity and higher equipment usage. The beam can even be split to allow simultaneous work in more than one work station.

Applications

An important industrial application is thin sheet welding of coated steels for automotive bodies. Typically speeds up to 10m/minute for lap joints and butt joints for tailored

2. A typical tailored blank is shown in Figure 3.

Welding of Aluminium alloys

High speed and low distortion welding techniques have been developed by TWI for sheets and extrusions for automotive, transportation and ships structures. Welding aluminium sheet is shown in Figure 4 and a welded extrusion is illustrated in Figure 5.

Gear Components

Low distortion high quality welds have been achieved in stainless steel rings for J J Harvey Ltd shown in Figure 6.

Steel structures

The welding of panels shown in Figure 7 results in lightweight structural steel panels which can be used in a range of applications including offshore and ship construction.

Thick section butt welding

Figure 8 bears an example of a butt weld achieved in two passes for a total steel thickness of 40mm. TWI is looking at the development of wire compositions for easier welding to improve weld properties for thick section joints.

Thick section laser cutting techniques

Figure 9 shows the quality of cut that can be achieved and offers possibility for reducing machining costs by using a combined laser cutting and then laser welding process. In production thicknesses up to 15mm can be cut but developments are underway to increase this to up to 80mm.

Nd:YAG laser welding

Currently commercially available systems are supplied with a power output of up to 2.5kW but developments are putting this up to 5kW. Nd:YAG lasers can be delivered to the workpiece by fibre optic cable which offers significant advantageous for 3D processing and remote access. Their maximum welding capabilities are much less than the $C0_2$ laser. Nd:YAG lasers can weld sections up to 10mm in thickness at speeds of up to 0.4 m/minute.

TWI's Nd:YAG laser system and robot manipulator is shown in Figure 10.

Historically Nd:YAG lasers have been used in microelectronics and electrical applications for package sealing and spot welding. Now the higher powers being utilised by the automotive and aerospace industries for welding of sheet materials in steels and aluminium alloys pushing further developments. It is expected that the next generation of Nd:YAG lasers could be applied to structural steel applications.

4. Electron beam welding

Electron Beam (EB) welding is a mature technology which has been applied extensively in the nuclear and aerospace industries for over 30 years. These application areas benefit from the reliable weld quality and accuracy achievable with the electron beam process and furthermore, by conducting the welding operation under high vacuum conditions with minimal heat input, satisfactory welding performance can be achieved in reactive metals and exotic alloys which are difficult to weld by conventional processes. Typical high vacuum ($\sim 10^{-3}$mbar) equipment is commercially available at power levels of up to 30kW which is capable of welding steel of up to 75mm thickness in a single pass. High power EB welding pioneered at TWI in the 1970's has progressed to an extent whereby welding of steel of up 150mm in thickness can be carried out with relative ease and systems have been developed with up to 200kW which can penetrate over 300mm in steel as shown in Figure 11.

In parallel with the high powered developments, the design of electron beam equipment has been refined to improve reliability and process control further and thus extend the range of applications of the process for single pass welding of heavy sections in critical applications.

In welding heavy sections structral steelwork for example in the offshore industry where high weld quality is required together with high joining rate, electron beam welding offers a cost effective solution as shown in Figure 12. Welding is achieved in a single pass without the need for pre-heating or a welding consumable.

However, high vacuum operation generally dictates that the workpiece is contained entirely in a vacuum chamber, thus the scope of application is limited by the size (and cost) of the vacuum chamber, the need for sophisticated vacuum pumps and the time required for evacuation. TWI's 150m^3 vacuum chamber is illustrated as an example of a typical large chamber installation in Figure 13. This machine is equipped with a 75kW electron gun and can be used effectively for welding either single large workpieces or for multiple loading of smaller parts. Figure 14 shows a series of eight 18mm thick aluminium alloy heat sinks for the railway industry assembled for welding in TWI's 150m^3 chamber. In this case, the welding time per component was less than two minutes and welding was achieved with minimal distortion.

Non vacuum and reduced pressure EB welding

In an attempt to improve weld cycle time, particularly in the automotive industry, equipment was developed in the 1970's to enable welding to be conducted, at atmospheric pressure, without the need of a vacuum chamber and using inert gas shielding to prevent oxidation of the weld pool. Commercial non vacuum electron beam equipment of 60kW power has become available and is used for high speed welding of relatively thin materials. However, because the electron beam is scattered readily in air, until recently, deep penetration was not achievable reliably. With new equipment developments in this area it is now possible to penetrate over 70mm in steel at atmospheric pressure, thereby extending the range of applications further to heavy engineering. Figure 15 shows a section of a non vacuum electron beam weld in 38mm carbon maganese steel produced using TWI's new 150kW NVEB facility. This equipment can operate at a range of pressures from atmospheric pressure to 10^{-3}mbar. Weld profile

profile and penetration can be enhanced by operating the equipment at reduced pressure (coarse vacuum) as shown by the example in Figure 16 which was produced at a pressure of approximately 1mbar. In consequence this illustrates that the system is ideal for use either in air or with a local vacuum system to enable welding of large scale, heavy section structures to be carried out.

5. Concluding remarks

Power beams are already being used extensively by some areas of manufacturing for welding and cutting. These industries have recognised the potential for EB and laser systems to offer high quality, low distortion welds at much higher production rates than conventional techniques.

In this age of rapidly developing technology it is increasingly necessary for companies to be aware of the potential impact of these new developments on their business. Laser and EB systems offer significant advantageous over the conventional technologies and manufacturers who ignore these developments may find themselves becoming uncompetitive.

Table 1. Summary of characteristics of CO_2 and Nd:YAG lasers for industrial production

PROPERTY	CO_2 LASERS	Nd:YAG LASERS
Lasing medium	$CO_2 + N_2 + He$ gases	Single crystal rod neodymium doped yttrium-aluminium garnet
Radiation wavelength	10.6µm	1.06µm
Excitation method	Electric discharge	Flash lamps
Consumables	$CO_2 + N_2 + He$ gases, Electricity	Flash lamps, electricity
Output powers	Up to 25kW (40kW)	Up to 3 kW (5kW)

() Lasers in development

Table 2. Summary of characteristics of CO, Excimer and oxygen/iodine lasers.

LASER TYPE	PROPERTY				
	Lasing medium	**Wavelength µm**	**Excitation method**	**Consumables**	**Output power kW**
CO	$CO/N_2/He/O_2$	5	Electric discharge	Gas, Electricty	5 (15)
EXCIMER	XeF	0.351	Electric discharge	Gas, Electricty	0.035
	XeCl	0.308			0.200 (1)
	KrF	0.248			0.150
	KrCl	0.222			0.01
	ArF	0.193			0.06
	F_2	0.157			0.003
OXYGEN/IODINE	O_2/I	1.3	Chemical	O_2/I	1

() Lasers in development

Table 3. Summary of capital costs for typical CO_2 and Nd:YAG lasers at different powers.

POWER LEVEL	LASER TYPE	
	CO_2	Nd:YAG
500W	£40,000	£80,000
1kW	£50,000	£120,000
2kW	£65,000 - £85,000	£150,000
5kW	£140,000 - £180,000	-
10kW	£400,000	-

Notes:

These costs are for the equipment alone and will vary dependent on supplier.

Table 4. Comparison of CO_2 and Nd:YAG lasers/handling systems for Three Dimensional Laser Processing (3).

COMBINATION LASER / HANDLING SYSTEM	Nd:YAG / ROBOT	CO_2 / GANTRY
Investment costs	Low	High
Running costs (laser)	High	Low
Floor space required	Low	High
Accuracy	Low	High
Beam guiding system	Easy	Complex
Accessability	Good	Bad
Workroom	Small	Big

Table 5. Running costs per hour for a CO_2 and Nd:YAG laser based systems designed for 3D welding of brass (4).

	LASER TYPE	
	CO_2	Nd:YAG
Total cost per hour	\$31.9 (100%)	\$36.3 (100%)
Depreciation	78.4%	67.3%
Floor space	6.7%	1.6%
Service	1.6%	7.5%
Electric power	6%	8%
Laser gas	3.6%	-
Flash lamps	-	10.8%
Process gas	3.6%	4.8%

Costs based on:

- 5kW CO_2 laser (RF excited) with a standard industrial robot carrying an external beam delivery system.
- 1kW pulsed Nd:YAG laser (10kW peak power) with a standard industrial robot and an optical fibre for beam delivery.

Table 6. Hourly rates and piece cost for CO_2 and Nd:YAG laser based systems for 3D welding of brass (4).

	LASER TYPE			
	CO_2 laser	Nd:YAG laser	CO_2 laser	Nd:YAG laser
One shift	154	114	2	2.4
Two shifts	93	75	1.3	1.6
Three shifts	73	64	1	1.4
Occupation time per part	49 secs	76 secs	-	-

Note:

All costs are presented in US \$.

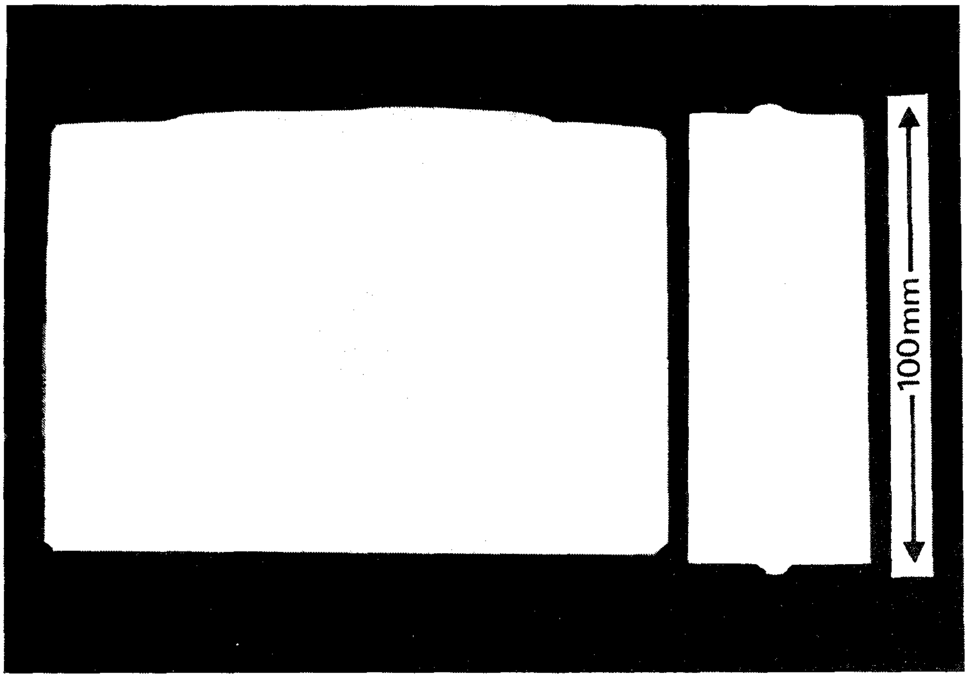

Fig 1 Comparison of multipass (>90) submerged arc weld with single pass EB weld in 100mm thick C–Mn steel

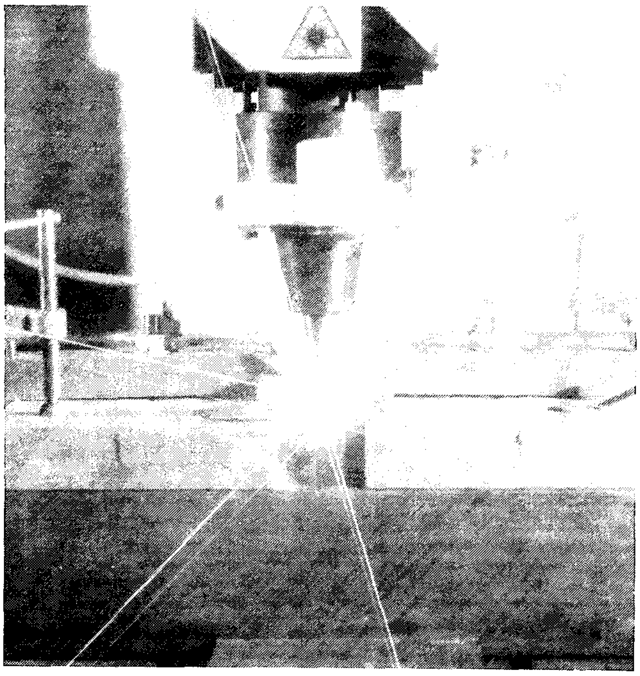

Fig 2 Thin sheet welding using CO_2 laser for lap joint in coated steel

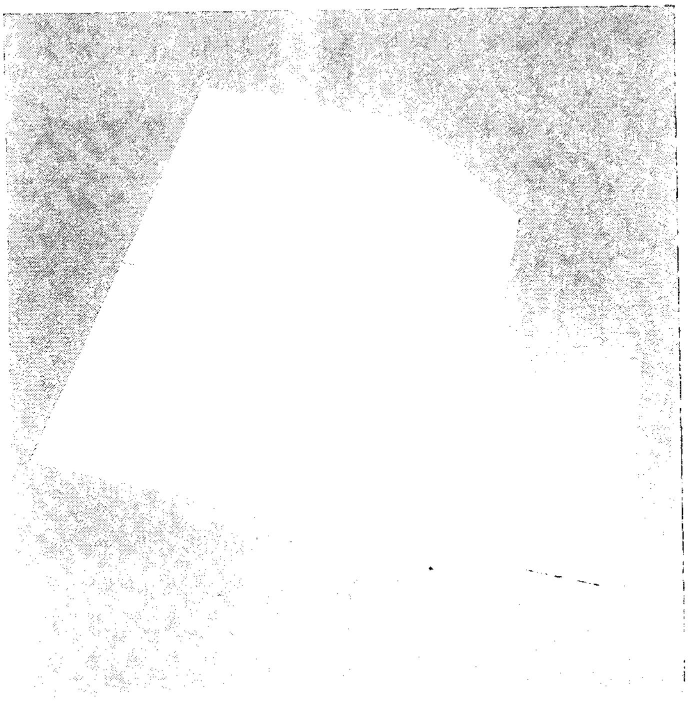

Fig 3 Example of laser welded "tailored blank"

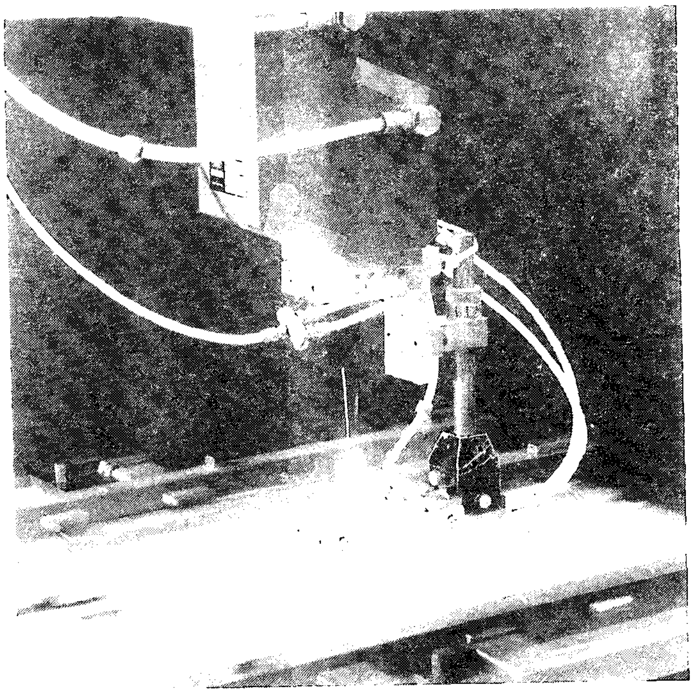

Fig 4 CO_2 laser welding of aluminium sheet

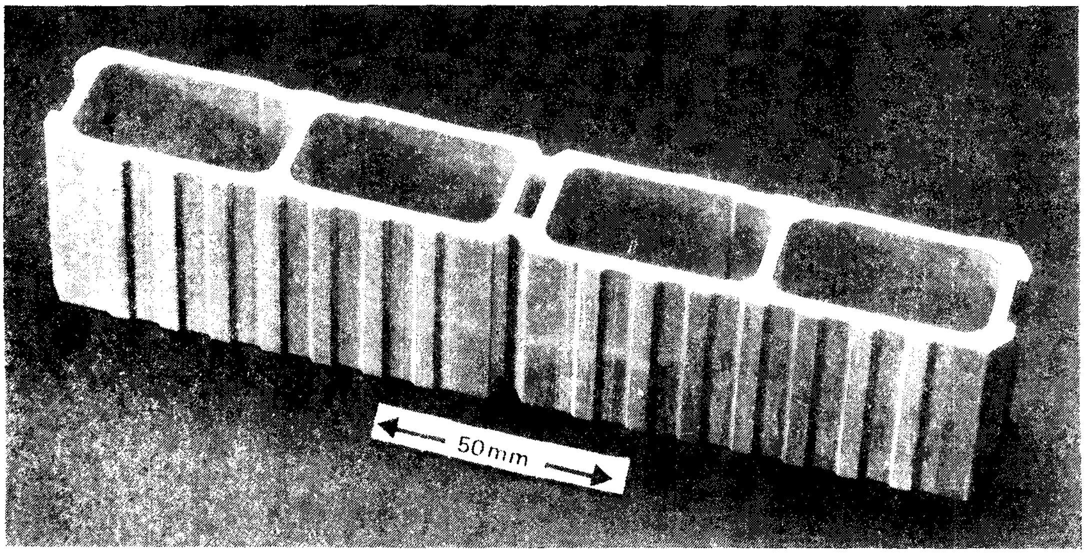

Fig 5 Laser welded aluminium extrusion

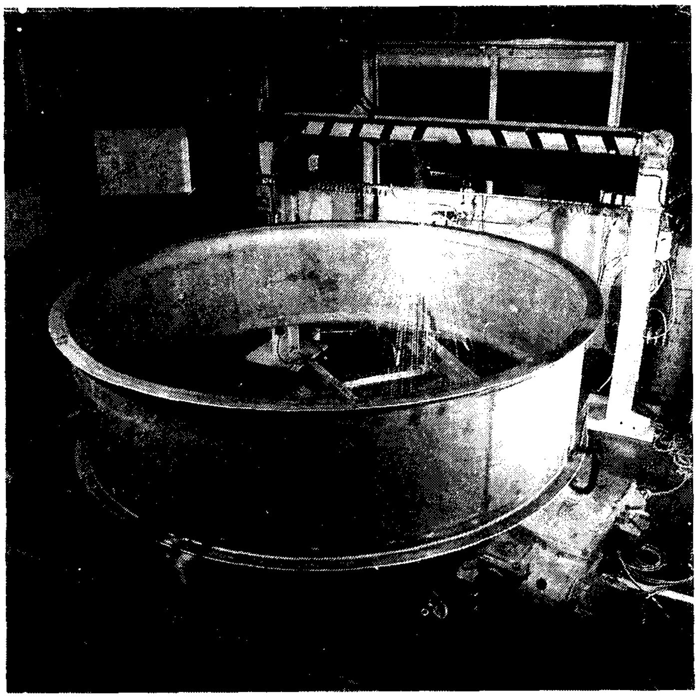

Fig 6 Stainless steel rings for JJ Harvey Ltd

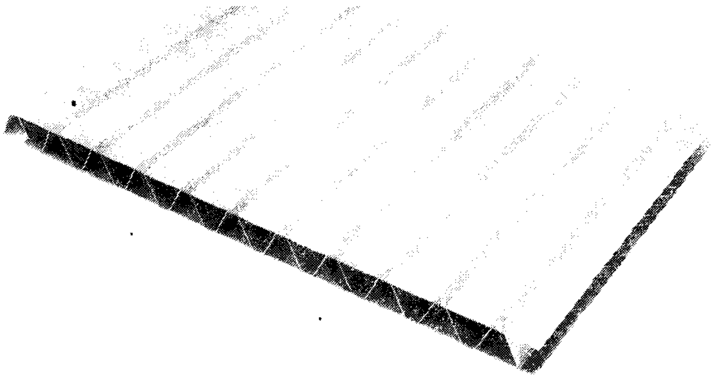

Fig 7 Laser welded lightweight steel panel

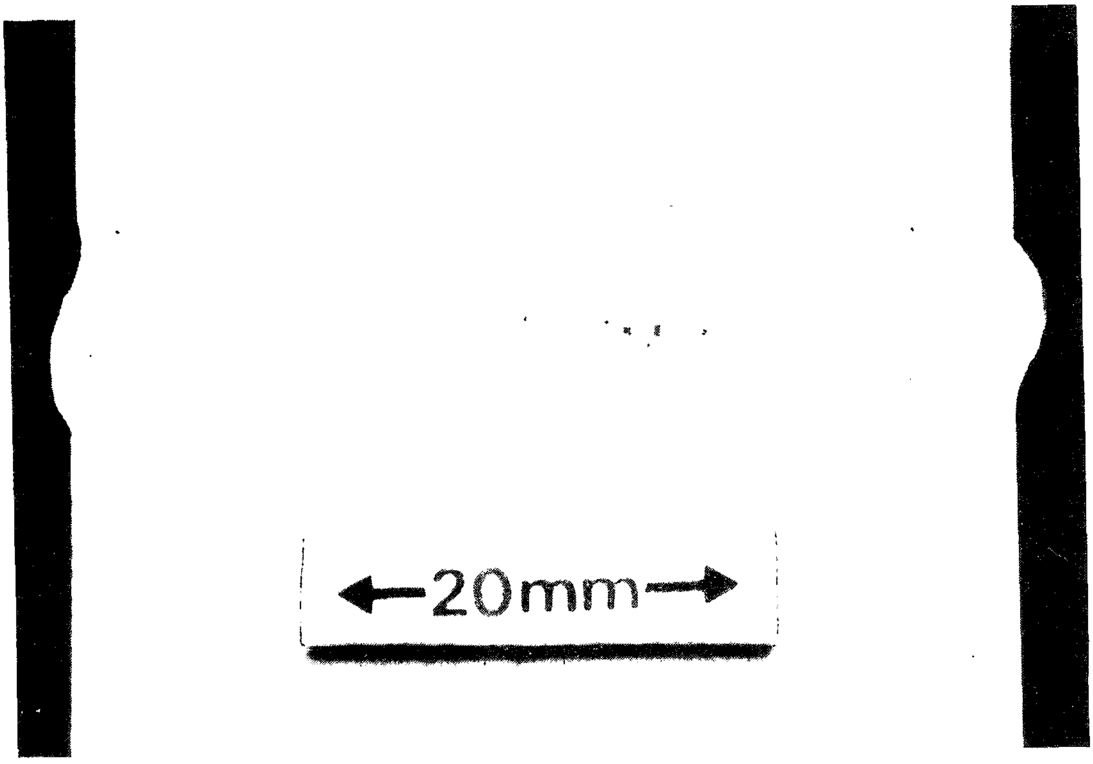

Fig 8 Butt weld in structural steel

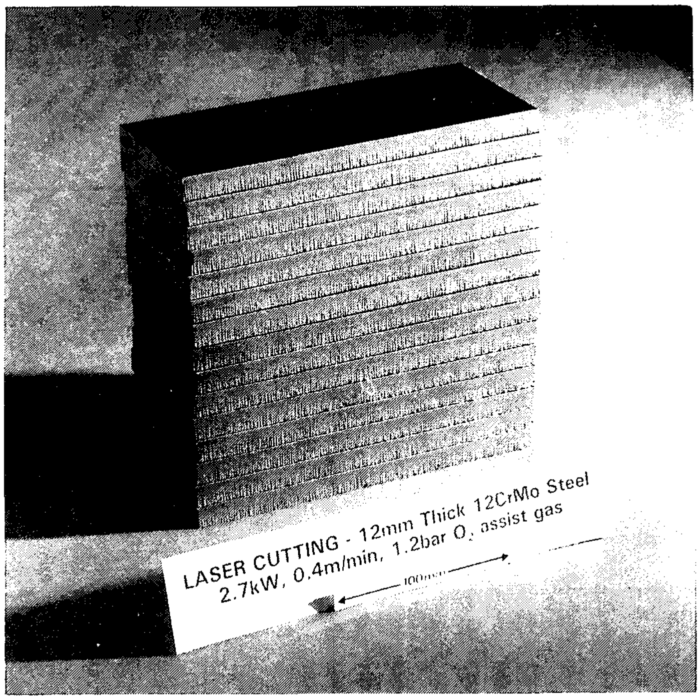

Fig 9 Thick section laser cutting samples

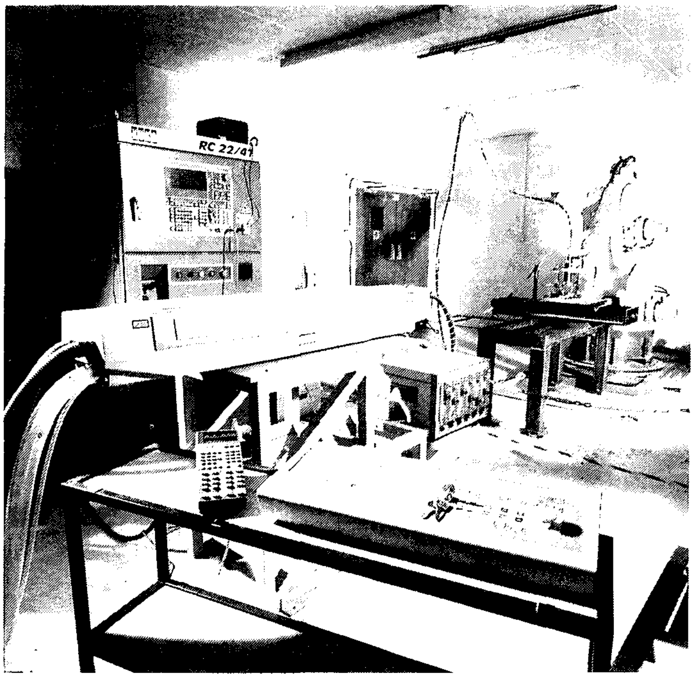

Fig 10 TWI's Nd:YAG laser system

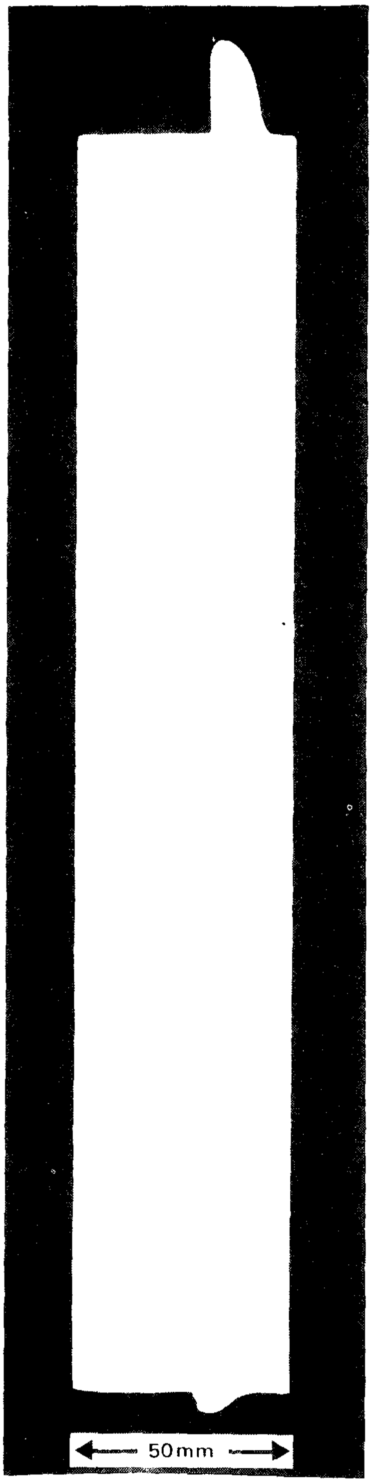

Fig 11 Single pass EB weld in 280mm thick C–Mn steel

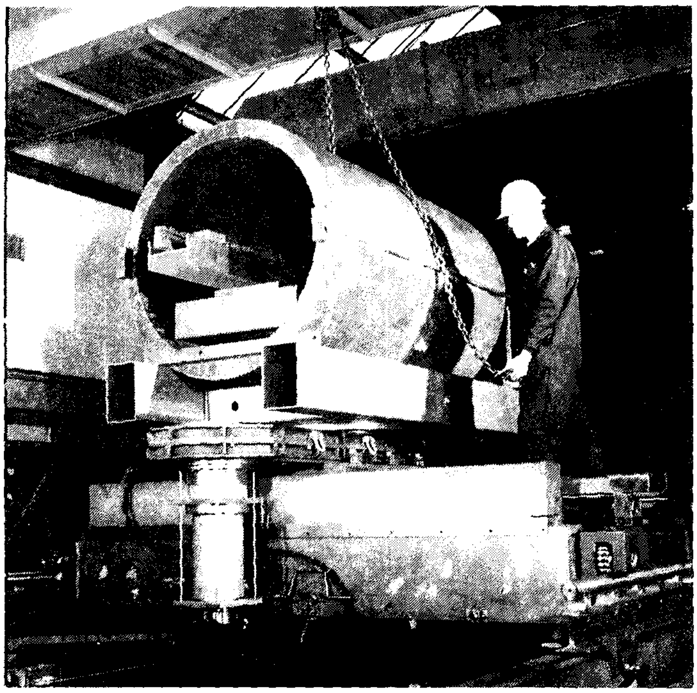

Fig 12 2.5m length, 100mm wall thickness tube EB welded

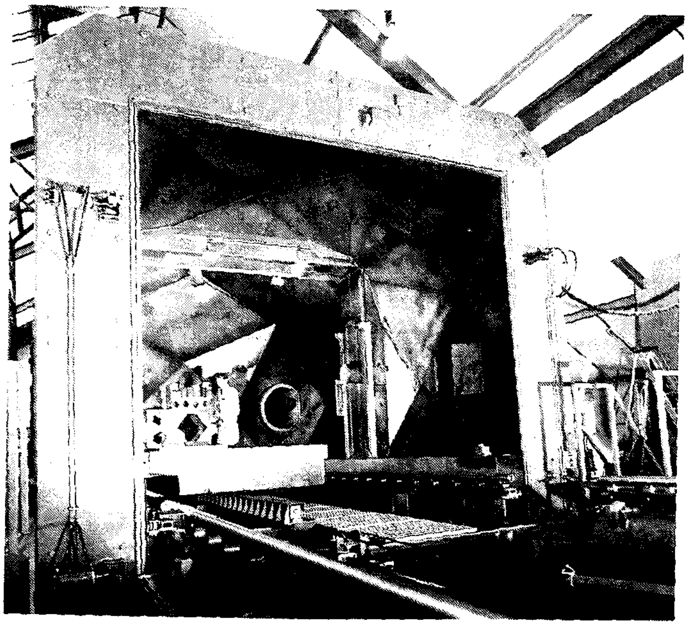

Fig 13 TWI's 150m^3 EB2 vacuum chamber

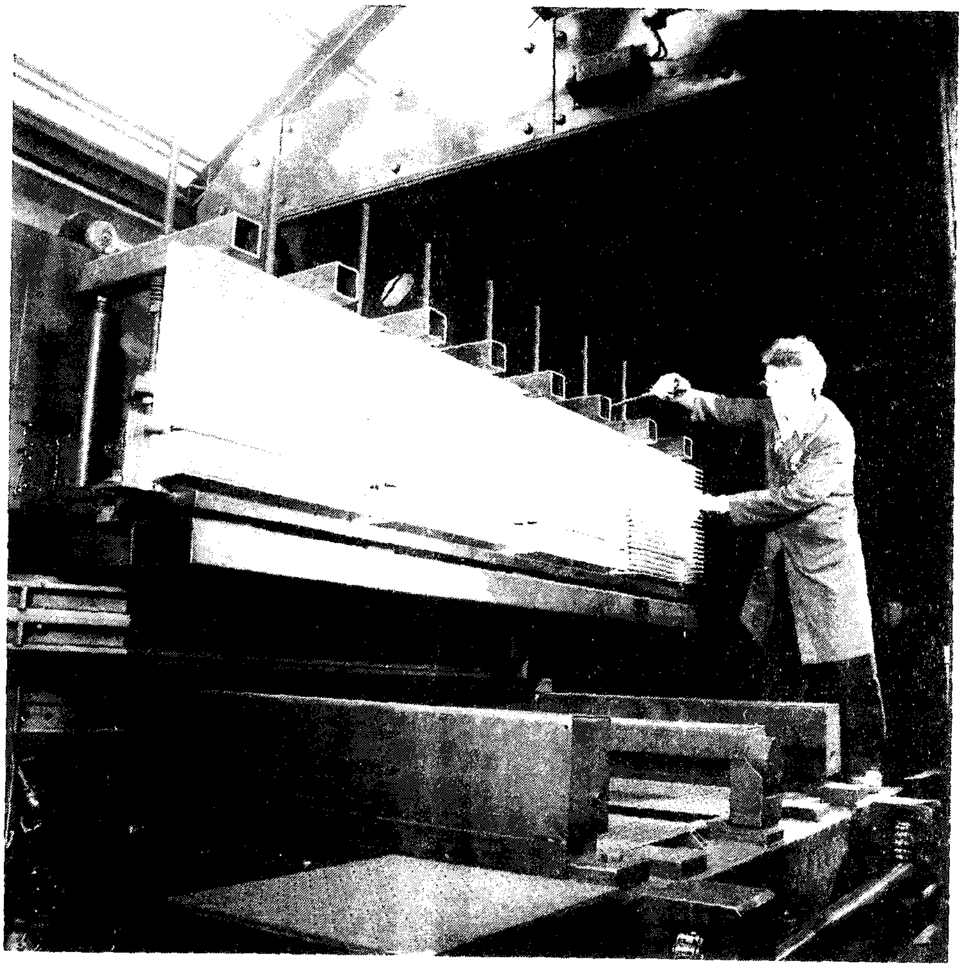

Fig 14 Multiple loading of aluminium heat sinks for EB welding

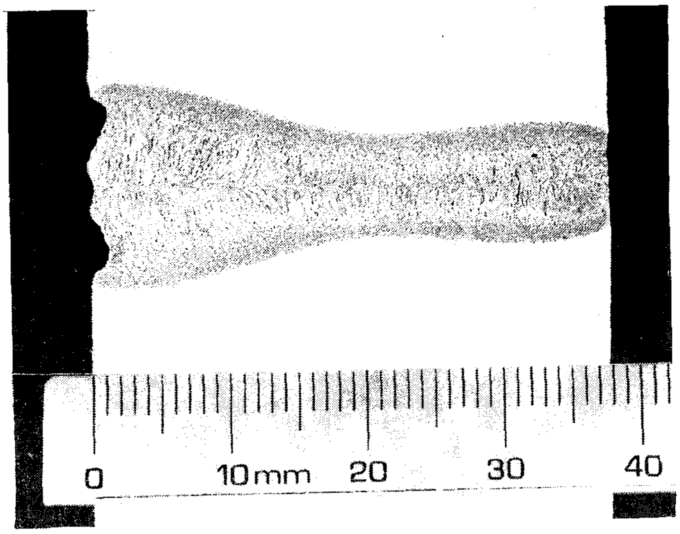

Fig 15 NV Electron Beam weld in 38mm C–Mn
Steel produced at atmospheric pressure

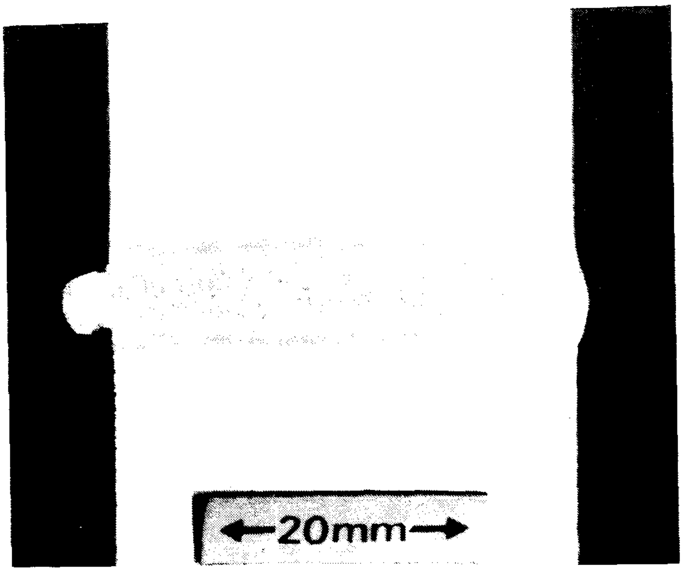

Fig 16 EB weld produces in 38mm thick C–Mn
steel with NVEB reduced pressure (1mbar)