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NOVEMBER 2002

EXECUTIVE SUMMARY:IMPROVED PRODUCTIVITY IN FUSION WELDING

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IMPROVED PRODUCTIVITY IN FUSION WELDING

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D S Howse

ABSTRACT

This document is an Executive Summary of individual submissions of work that the author has submitted towards the degree of Engineering Doctorate. The work comprises three main themes, which can be demonstrated in a broader sense as contributing towards improved productivity in fusion welding:

i) The use of active fluxes for Tungsten Inert Gas (TIG) welding.
ii) An investigation into the reduction of porosity when Metal Active Gas (MAG) welding galvanneal coated steel sheet used in the automotive industry.
iii) The use of high power Nd:YAG laser welding for the production of large diameter, long distance land pipelines.

Active fluxes give improved productivity by increasing the penetration depth of the TIG welding process by the simple addition of a flux applied to the surface. Although the productivity benefits of the process had been proven through a joint TWI/industry project, the mechanism by which the fluxes produced this improvement was not fully understood. The first theme investigated the mechanisms at work in providing increased penetration and concluded that the primary mechanism responsible for the action of the fluxes was not due to a change in the flow of the molten pool but, as others had suggested, due to arc constriction. This work contributed to a greater understanding of the welding process and, furthermore, a greater understanding of the potential opportunities and limitations of the process when designing new fluxes for other alloy systems.

MAG welds in coated steel sheet used in the automotive industry are prone to porosity leading to high reject rates. The second phase of work reported here determined welding procedures capable of delivering low porosity welds developed through statistical experimental design. These procedures demonstrated how low porosity welds could be made using conventional MAG welding techniques on steels that had been galvanneal coated to provide corrosion resistance. The procedures developed could be easily implemented at high production rates in an industrial manufacturing environment to reduce defect levels, and thus costly repairs or high scrap rates.

The third theme of the work demonstrated how Nd:YAG laser welding could potentially be used to replace conventional arc welding techniques for land lay of gas transmission pipelines. The application of a single laser fill pass, made at high production rates, could replace the use of multiple MAG welding stations greatly reducing the costs associated with pipeline fabrication. BP has claimed that half pipeline cost savings of up to $300 million dollars are achievable through the implementation of such a technique. The justification for the use of lasers in pipelines is discussed in terms of both technical and economic suitability. Preliminary experimental work showed that high power Nd:YAG laser welds could achieve productivity targets, although in order to reduce defects and achieve the necessary structural performance it would be necessary to combine laser welding with a MAG welding process.

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The work carried out on Nd:YAG laser welding of pipelines was funded by CRC Evans International and BP. The assistance of A Hassey in making the laser welds is gratefully acknowledged. The author would like to acknowledge the contribution of I Hadley in organising the Charpy impact testing work and providing analysis of the results and P Hart in providing the analysis of the metallographic sections.

DECLARATION

All of the work reported in this document is the work of the author except where acknowledged or referenced. For all of the work reported here, the author was the designated project leader within TWI. As such, the author was solely responsible for setting the objectives for the work in agreement with the industrial partners involved, planning and progressing the experimental work, analysing and providing interpretation of the results and reporting.

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GLOSSARY OF TERMS

Autogenous welds:	Welds made without consumable filler additions.
A-TIG:	TIG welding with activated fluxes.
Arc energy:	Energy of the arc before losses through reflection or radiation. Expressed in kJ/mm.
Cap:	The visible fused top part of a weld bead.
Carbon equivalent value (CEV):	A value derived from certain elements alloyed with iron to produce steel, giving an indication of hardenability during a weld thermal cycle.
CO_2 laser:	Laser producing an infrared light of wavelength 10.64 μm by excitation of a gas mixture containing CO_2.
Conduction limited welding:	Shallow penetration welding where the rate of heat conducted away by the surrounding material limits the size of the molten pool.
Dip or short circuit transfer:	Metal transfer across the arc where the arc is continuously short-circuited and re-ignited. Usually occurring at low currents.
Galvanneal coating:	Zinc coating converted to a zinc-iron alloy by passing through a heated chamber directly after leaving the zinc coating bath.
Heat input:	Heat energy transmitted to the parent material from the heat source after losses through reflection or radiation. Expressed in kJ/mm.
Keyhole welding:	Deep penetration welding achieved by a concentrated heat source creating a cavity surrounded by molten material that is passed through the material being welded.
MAG:	Metal Active Gas.
Nd:YAG laser:	Laser producing an infrared light of wavelength of 1.064 μm by exciting a crystal of Neodymium doped Yttrium Aluminium Garnet.

Penetration Bead:	The visible fused underside portion of a fully penetrating weld.
Solidification cracking:	Internal cracking caused by tearing of low ductility segregated regions during solidification of the molten pool.
TIG:	Tungsten Inert Gas.

1. INTRODUCTION

TWI is an independent research and technology organisation, which specialises in providing services to industrial members from a wide range of industrial sectors related to joining technology and associated engineering. As such, the joining technologies covered are extremely wide ranging.

Most engineering structures require that individual parts be joined together to form a whole part. For steel structures, fusion welding is often used to provide a joint with equal or greater structural integrity than the individual parts. However, in making the joint by this method, defects can be introduced which require the parts to be either scrapped or repaired. Also, the process of fusion welding involves time and effort, and therefore cost.

The work submitted to make up the Engineering Doctorate portfolio covered three specific areas:

i) The use of active fluxes for Tungsten Inert Gas (TIG) welding.

ii) An investigation into the reduction of porosity when Metal Active Gas (MAG) welding galvanneal coated steel sheet used in the automotive industry.

iii) The use of high power Nd:YAG laser welding for the production of large diameter, long distance land pipelines.

All of the three subjects above relate to improved productivity in fusion welding through either reduction in defects, or by making welds in a more efficient, and therefore more economical, manner.

Active fluxes for TIG welding increase the penetration of conventional TIG welds, enabling steel up to 6mm thickness to be welded in a single welding pass. The flux is applied by hand to the surface of the material to be welded in a thin layer of less than 0.5mm thickness. Using conventional autogenous TIG welding equipment and procedures, a deep penetration weld can then be made. Using conventional TIG welding techniques without fluxes, the penetration of the process is limited to a few millimetres and requires a number of passes to make a welded joint in thicker steels. The use of fluxes can, therefore, give much higher production rates while not compromising the high quality of conventional TIG welding. Within the work reported here, the mechanisms producing the A-TIG effect were investigated by carrying out welds on stainless steel, using a range of current carrying, and non-current carrying, fusion welding techniques. The effect of the fluxes in producing deep penetration welds varied greatly depending upon the fusion welding technique used. Through analysis of the results, it was possible to isolate potential mechanisms for the increased penetration effect of the active fluxes when TIG welding, and deduce which had a dominant effect.

As the use of higher strength, thinner steels are required for automotive fabrication in order to reduce vehicle weight, and so meet future legislative requirements for emissions, so the need to provide adequate corrosion resistance becomes even more important. Coating the steel with a thin layer of zinc usually provides this corrosion resistance. Also, as the material is thinner, component fabricated parts require continuous joints to stiffen up the structures rather than conventional point joining. One method of arc welding commonly used to produce continuous joints in sheet materials is MAG welding. However, when using MAG welding, any zinc coating on the steels will melt and evaporate in the molten pool leading to porous welds. This commonly leads to very high rejection rates. The work described here investigated novel weld procedures using existing MAG welding technology to allow zinc coated steels to be welded at high production rates. The procedures produced welds with a low and acceptable porosity content, which also demonstrated acceptable mechanical properties.

Overland gas transmission pipelines are currently manufactured using a multipass MAG process. Each individual pass is produced at a single welding station, which gradually moves along the pipeline being fabricated. The pipeline spread, as it is known, can comprise eleven separate welding stations depending upon the wall thickness of the pipe being welded. Laser welding produces deep penetration welds with the capability of replacing a number of these individual welding stations. Furthermore, the recent development of high power (>4kW) Nd:YAG lasers has opened up new opportunities for flexible manufacture by delivering the laser light through fibre optic cables. The work reported here investigated the possibility of replacing a number of individual MAG welding stations with a single high power, deep penetration Nd:YAG laser welding station, thus greatly reducing the costs of pipeline manufacture. Practical work was carried out with 8.2kW of Nd:YAG laser power at the workpiece on a representative pipeline steel. This work highlighted the need for combining the Nd:YAG laser with a MAG welding process to produce a hybrid process which would give acceptable weld metal properties.

The individual submissions that make up the portfolio are summarised in Table 1. This executive summary will discuss in detail each of the three themes contributing to improved productivity in fusion welding.

Table 1 Overview of submissions to the portfolio.

Submission	Issues	Main Research Method	Outcomes/Achievements/ Innovations
1. An investigation into the mechanisms of active fluxes for TIG (A-TIG) welding.	To determine the primary mechanisms producing altered welding characteristics using A-TIG fluxes.	Literature review and the use of arc and other fusion processes and analysis of the results to isolate potential mechanisms responsible for increased penetration.	The work demonstrated that the primary mechanism producing increased penetration was arc constriction rather than surface tension driven molten pool flow.
2. Metal active gas (MAG) welding zinc coated steels for automotive applications: a review of literature.	To identify objectives and potential solutions for producing low porosity welds in zinc coated steels used in the automotive industry.	Literature review.	The work defined targets for the welding process in order that any solution would be capable of being implemented in an industrial environment.
3. Metal active gas weld procedure development for galvanneal coated high strength steel sheet.	To produce guidelines for making MAG welds in galvannealed zinc coated steels with low porosity at optimum productivity and with reduced distortion.	Statistical experimental design, analysis of results and empirical development of welding procedures.	Development of novel MAG welding procedures for zinc coated steels delivering low and acceptable porosity suitable for industrial implementation.
4. Nd:YAG laser welding for land lay of pipelines: a review of literature.	To review existing literature relevant to high power Nd:YAG laser welding with particular reference to land lay of C-Mn steel pipelines.	Literature review.	The work demonstrated that laser welding was not only technically and economically feasible, but would lead to significant cost reduction for land lay of pipelines. The work also proposed solutions to potential practical problems.
5. An investigation into the practical application of high power Nd:YAG laser welding for girth welding of pipelines.	To provide a preliminary assessment of the suitability of high power Nd:YAG laser welding of pipeline steels.	Laser welding trials and metallurgical and property assessment.	The work demonstrated that hybrid Nd:YAG laser/ MAG welding was capable of producing sound welds whilst meeting production targets for land lay of pipelines.

2. THE USE OF ACTIVE FLUXES FOR TUNGSTEN INERT GAS (TIG) WELDING

2.1. BACKGROUND

2.1.1. Tungsten Inert Gas Welding

Tungsten Inert Gas (TIG) welding is a widely used welding process by which an arc is struck between a non-consumable electrode and the workpiece creating the heat to make the joint (Fig. 1). The main advantage of the process is to produce high quality welds, but it also has two major limitations. The first is that the deposition rates are lower than other consumable electrode arc welding processes, and that, for stainless steels, the parent material composition can affect the depth of penetration achieved by altering the flow of the molten pool during welding (1). The TIG process can be used autogenously, i.e., without filler, or with a consumable filler wire addition. The process also operates in conduction limited mode, i.e., it does not produce a keyhole, and the shape of the weld pool is limited by the conduction of heat from the arc through the material being welded. As such, the

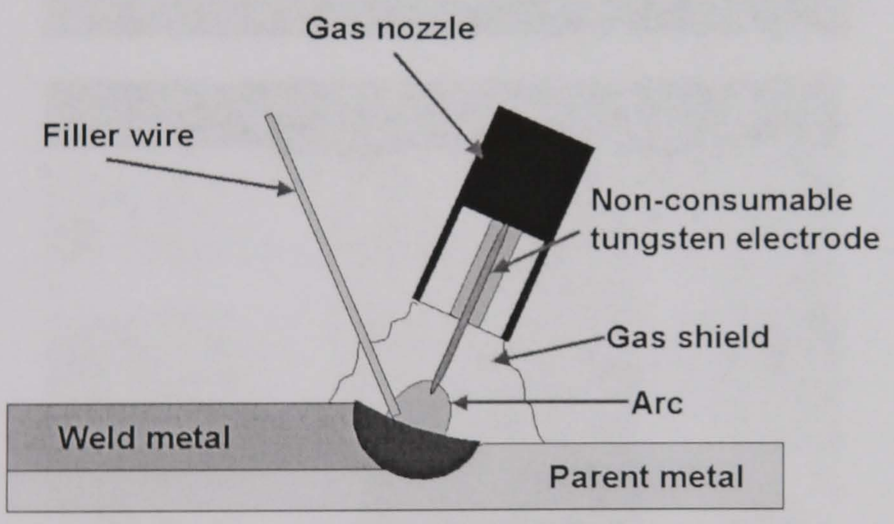

Fig. 1 Schematic of the TIG welding process.

penetration depth of the process is limited and deeper penetration welds can only be achieved by using higher welding currents which produce larger molten pools. These are difficult to control and shield whilst welding. Penetration depth is important in that thicker sections can be welded in a single pass thus reducing costs.

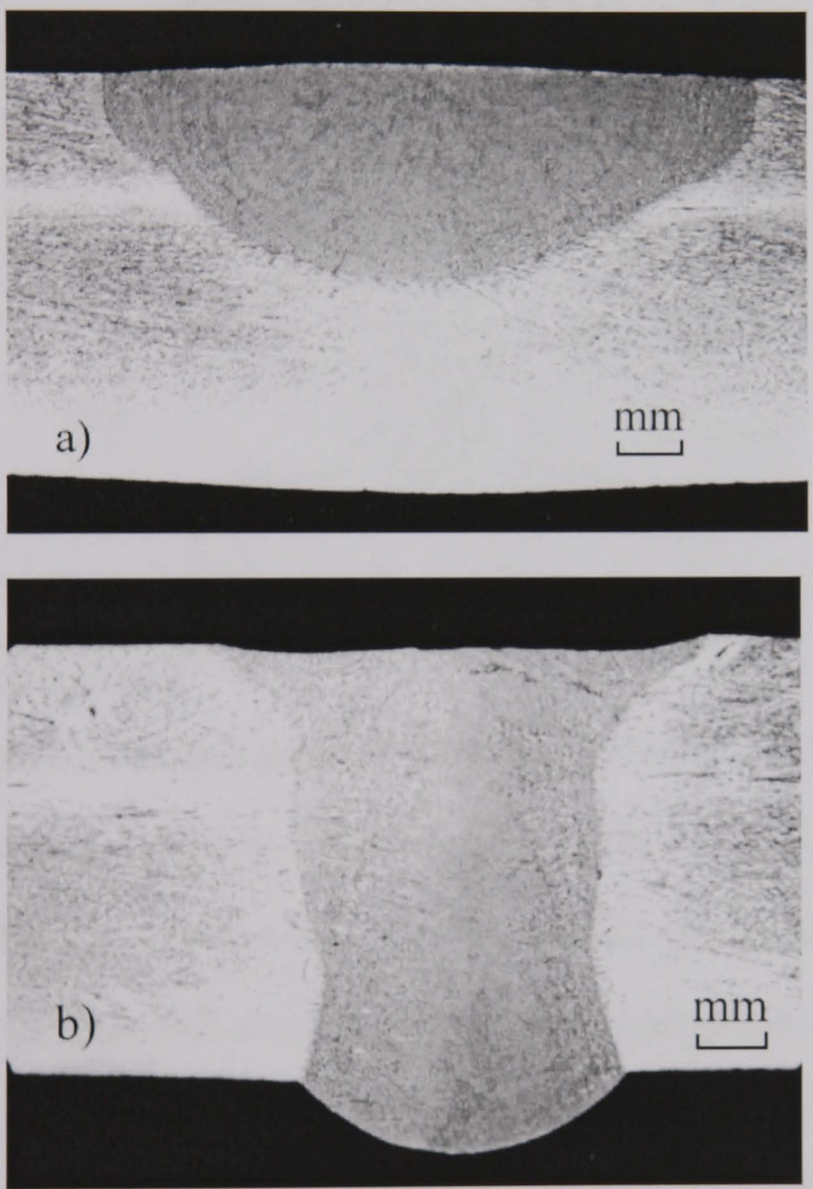

Fig. 2 Effect of the A-TIG flux on TIG welding penetration for 6mm austenitic stainless steel sections etched in 20% sulphuric acid solution:

a) Conventional TIG weld in argon at 187A, 9.5V, 100mm/min and 1.07kJ/mm arc energy;

b) TIG weld with A-TIG flux AFP SS1 in argon at 187A, 10V, 100mm/min and 1.12 kJ/mm arc energy.

2.1.2. Active Fluxes

Active fluxes (A-TIG fluxes) that increase the penetration of TIG welds offer a means of significantly increasing the productivity of the welding process, and are capable of welding up to 6mm thickness carbon manganese or stainless steels in a single pass, without filler material (Fig. 2). Using the conventional TIG process, six passes or more would be required, and in order to gain access to the first or root pass an angled preparation would have to be made. This would then require a filler wire to be introduced for subsequent fill passes (2). Although the flux enables the weld to penetrate to a thickness of up to 12mm (3), the molten pool will require support while the weld is made. Without this support, the weld bead will sag and have an unacceptable profile. Clearly, there is a limit in terms of the thickness of joint that can be welded in a single pass requiring no backing or support, i.e., a weld supported by the material's own surface tension. This will determine whether orbital, tube to tube welds can be made in a single pass. Work had previously been carried out by the author to establish the maximum thickness limit for a number of conditions and these results are shown in Table 2 (2). Table 3 also shows comparative costings (per metre of weld) when welding 6.0mm stainless steels with conventional TIG welding and with active fluxes. The data were calculated using TWIs Weldcost software, version 1.01, 1986. It can be seen from the figures in Table 3 that the greatest cost saving associated with the use of A-TIG fluxes is in labour, although savings are also made through no filler wire being required.

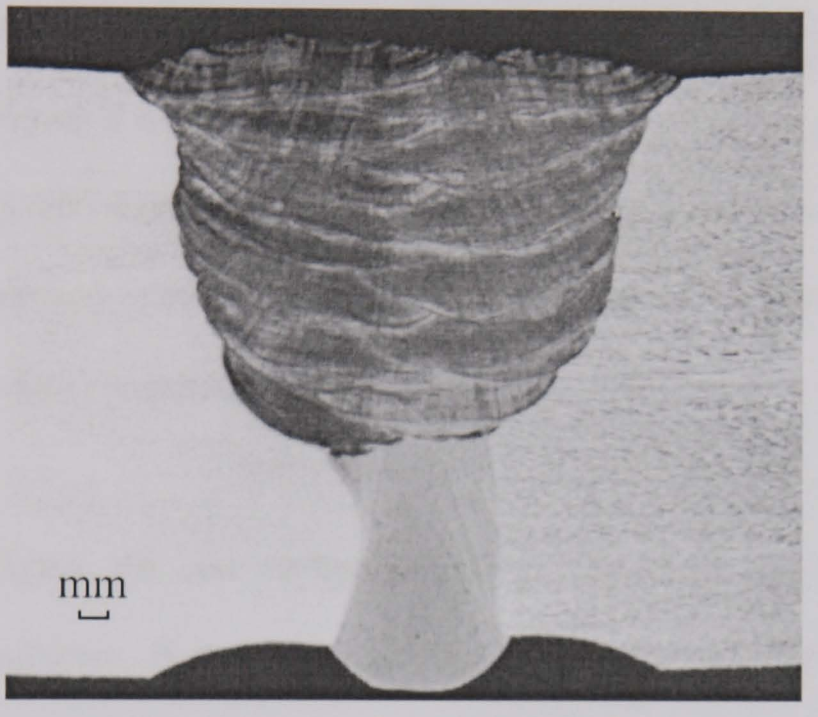

Fig. 3 Butt weld in 20mm thickness stainless steel with 7mm A-TIG root pass etched in 20% sulphuric acid solution.

If this costing, based on using a typical commercial flux, were applied to a typical component such as a tube weld in 6.0mm thickness stainless steel with outside diameter 100mm, the cost of welding would be £4.15 per weld compared to a cost of

£9.39 for conventional TIG welding.

In addition to increased penetration, another possible application of the fluxes is to reduce the amount of filler material required to make a joint in thicker section material. Figure 3 shows a macrograph of a weld made in 20mm thickness stainless steel. The A-TIG root face was 7mm thickness and welded in a single pass. This reduced the amount of subsequent filler material required to make the joint by approximately 30% when compared to a conventional TIG root.

Again, the cost savings can be calculated for this component using the Weldcost software. If it is assumed that for conventional TIG welding, five additional weld passes would be required to complete the joint, the cost of making these passes would be £29.88. The cost of producing a deep penetration root pass with the A-TIG process would be £13.44 resulting in a per metre cost saving of £16.44.

Table 2 Maximum wall thickness of tube weldable in a single fully penetrating pass with A-TIG flux (2).

Joint type	Maximum thickness
Orbital tube to tube weld Stainless steel Welding position: pipe axis fixed horizontal Continuous Current	6.0mm
Orbital tube to tube weld Stainless steel Welding position: pipe axis fixed horizontal Pulsed Current	5.75mm
Root pass in butt joint Stainless steel U preparation Welding position: flat Continuous current	7.0mm

Table 3 Costing analysis of conventional mechanised TIG welding compared with A-TIG welding for 6.0mm thickness stainless steel.

Item	Cost £/m	
	Conventional TIG	A-TIG
Argon shielding gas	0.82	0.31
Welding wire	3.05	-
Labour (£20.00 per hour)	25.64	5.13
Plant	0.32	0.06
Power	0.04	0.02
A-TIG flux	-	8.00
Total	**29.87**	**13.21**

The A-TIG process is not susceptible to the problems caused by material (cast to cast) variations normally encountered when welding austenitic stainless steels (1). With A-TIG fluxes, is possible to weld a wide range of material casts in austenitic stainless steel using the same welding procedure, including modern 'cleaner' steels containing, for example, low sulphur and high calcium levels (1).

As active fluxes became available outside the former Soviet Union in the mid 1990s, TWI formed a partnership with the EO Paton Institute of Electric Welding (PWI) to further investigate their use for industrial applications. A project was initiated whereby interested industrial members of TWI funded a programme of work with a budget of £156,000 through individual contributions. The project was led by the author and had the objectives of identifying practical applications of active fluxes for C-Mn and stainless steels. For this work a range of procedures were developed and tested to provide qualification to current European and industrial standards and investigations were carried out into the repeatability and robustness of the process. Procedures were developed for a range of plate and pipe materials and also for manual and automatic welding techniques (4).

In addition to the industry related aspects under examination in this project, a second project was initiated, also led by the author, to identify the fundamental mechanisms of A-TIG flux welding, and lead to more effective ways of exploiting the technology. It is this work which formed the basis of an Engineering Doctorate submission to the portfolio (5). At the time of starting this project, fluxes were only available for C-Mn and stainless steels. It was thought that if the mechanisms of the process were better understood, new fluxes could be designed for alternative materials such as titanium or nickel based alloys. Another potential application of the fluxes was to enhance other processes such as Metal Active Gas (MAG) by improving penetration or stability in oxygen free shielding gases.

2.2. MECHANISMS FOR THE A-TIG PROCESS PROPOSED IN THE LITERATURE REVIEW

A-TIG fluxes were first utilised in the late 1950s by the E O Paton Institute of Electric Welding (PWI) in the former Soviet Union. The first published papers (6, 7) described the use of the fluxes for welding titanium alloys by submerged arc. The first reference to the use of the technology for steels was in 1968 (8).

Mechanisms had been proposed to account for the observation that the arc visibly constricts in the presence of an active flux (Fig. 4). It had been suggested that the concentrated arc energy either increased weld penetration through a molten pool

(Marangoni flow) or through an arc constriction mechanism (10, 11) although there was no generally accepted model. These two proposed models will be discussed in 2.2.1 and 2.2.2 respectively.

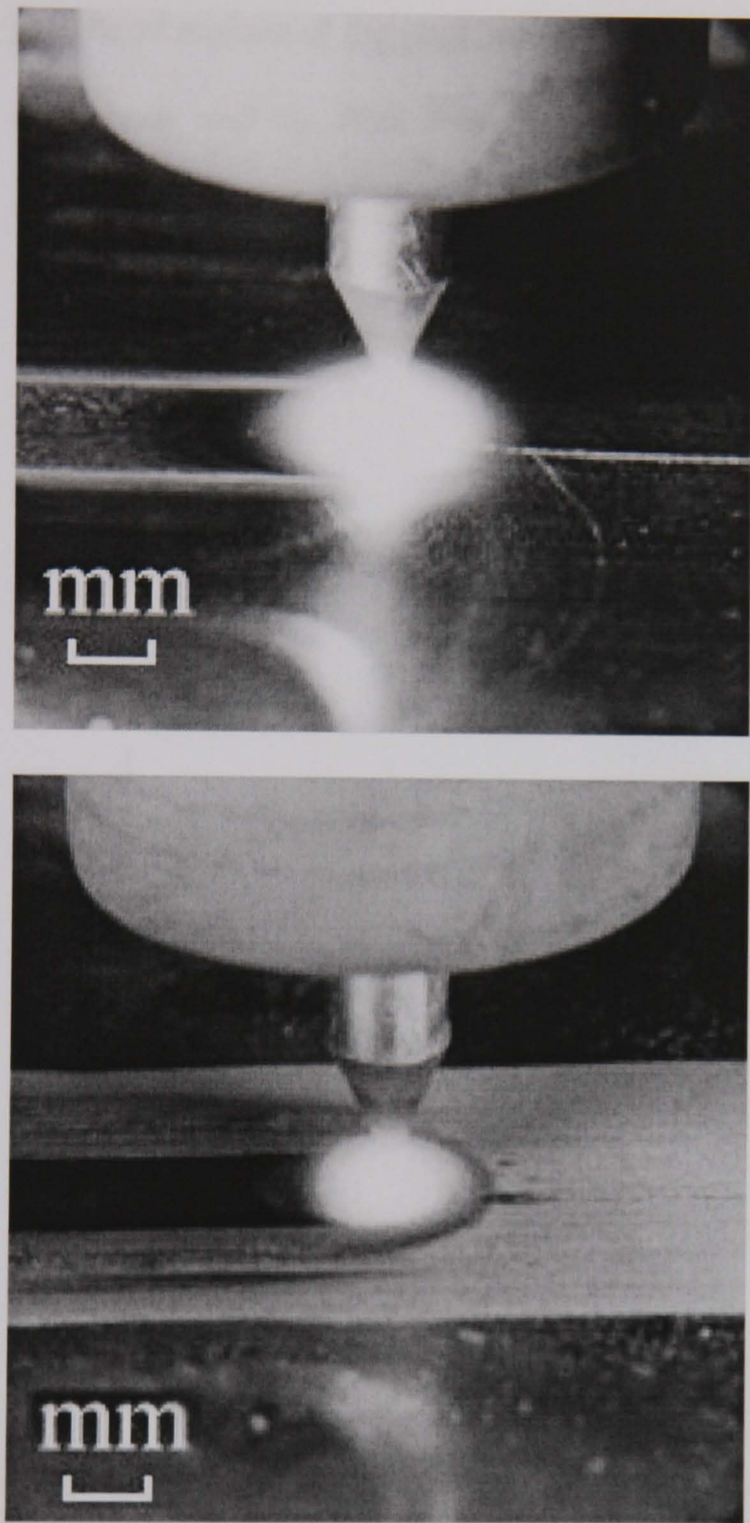

Fig. 4 Effect of the A-TIG flux on the TIG welding arc showing constriction:

a) Conventional TIG weld in argon at 187A, 9.5V, 100mm/min and 1.07kJ/mm arc energy;

b) TIG weld with A-TIG flux AFP SS1 in argon at 187A, 10V, 100mm/min and 1.12kJ/mm arc energy.

2.2.1. Marangoni Flow

The first proposed mechanism is based upon a weld pool flow mechanism due to the Marangoni flow effect on the weld pool (Fig. 5). This theory, which is thought to explain variable penetration in welds made without arcs (such as laser and electron beam welds) as well as TIG welds is centred upon variable penetration being caused by a change in fluid flow within the molten pool (9). This change in fluid flow is related to the Thermal Coefficient of Surface Tension (TCST) of the molten pool. If the gradient of the TCST is negative, the cooler peripheral regions of the pool will have a higher surface tension than the centre of the weld pool, and the flow will be outwards creating a wide shallow weld pool. In materials with a positive gradient, this flow is reversed to the centre of the weld pool, and in the centre the molten material flows down (10). This creates a narrower, deeper weld pool for exactly the same welding conditions. For stainless steels, sulphur can change the sign of the temperature versus coefficient of surface tension slope and hence alter the penetration depth of the resulting weld. Other elements, such as calcium or aluminium, also affect penetration, and it has been suggested that these tie up the elements affecting TCST, such as sulphur, rather than having a primary effect themselves (12). However, it should be noted that the change in weld bead shape usually associated with Marangoni weld pool flow (10) does not cause a change in weld bead shape of the same order as that seen when A-TIG fluxes are used.

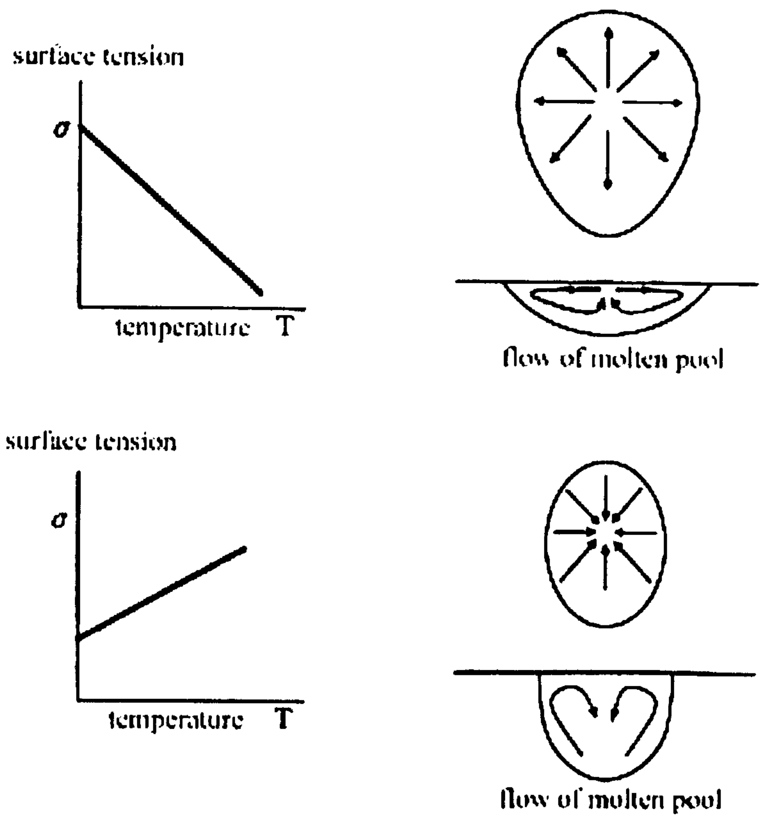

Fig. 5 Marangoni flow: (10)

a) Negative coefficient giving shallow penetration;

b) Positive coefficient giving deep penetration.

2.2.2. Arc Constriction

For the second mechanism, which was based upon arc constriction (11), it was proposed that the vaporised flux would constrict the arc by capturing electrons in the outer regions of the arc (Fig. 6), in a similar manner to a previous mechanism proposed by Simonik (13).

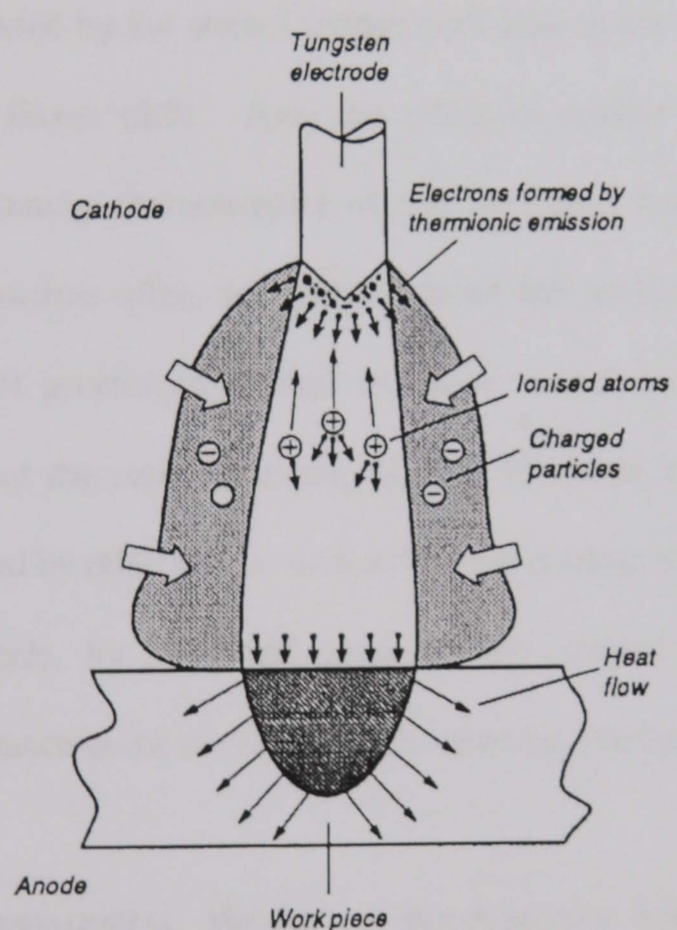

Fig.6 A-TIG mechanism by arc constriction.

The electrons in the outer regions of the arc attach to vaporised molecules and dissociated atoms to form negatively charged particles. This electron attachment can only take place in the cooler peripheral regions where the electrons have low energy and are in a weak electric field. Towards the centre of the arc, where there is a strong electric field, high temperatures and very high energy electrons, ionisation will dominate. Thus, this will restrict the current flow to the central region of the arc, which will increase the current density in the plasma and at the anode, resulting in a narrower arc and a deeper weld pool.

There were, therefore, two theoretical mechanisms proposed for the action of the A-TIG fluxes in producing deep penetration welds and a need for experimental work to be carried out to determine the primary mechanism at work.

It should be noted that neither mechanism is likely to offer a complete explanation for the effect of the fluxes in producing deep penetration welds. In terms of Marangoni flow, the effect is well documented, but the degree to which the penetration is increased by the altered molten pool flow is not of the same order as seen for the A-TIG fluxes (2,9). Also the effect is usually used to explain a decrease in the penetrating characteristics of the arc rather than an increase. The arc constriction mechanism offers an explanation of the visible constriction of the arc and hence, deeper penetration through increased current density by reducing the cross sectional area of the current carrying plasma. However, the same constriction effect could be caused by other effects such as thermal cooling of the external regions of the arc or, for example, by producing areas on the surface of the molten pool with increased resistance to the current flow and directing the current to the centre of the molten pool.

2.3. EXPERIMENTAL WORK TO INVESTIGATE THE MECHANISMS FOR THE A-TIG PROCESS

The following experimental work was carried out to investigate the proposed mechanisms for the A-TIG flux. The programme of work was designed to provide a comparison of the A-TIG effect with other deep penetration arc/plasma techniques, both current and non-current carrying. The Maragoni flow mechanism will occur in non-current carrying welding processes as well as current carrying processes. The arc constriction mechanism can only apply where there is an arc or plasma. The intention was to use the flux in combination with welding techniques giving increased penetration and compare with conventional TIG welding in order to draw conclusions regarding the A-TIG mechanism. All of these welds were made on a 6mm austenitic stainless steel containing low sulphur (Table 4) using the stainless steel active flux AFP SS1.

Table 4 Chemical analysis (wt%) of 6mm thickness austenitic AISI 316L steel used for A-TIG weldability trials (TWI report number S-96-208).

C	S	P	Si	Mn	Ni	Cr	Mo	V	Cu	Co
0.02	0.005	0.028	0.40	1.29	11.2	17.0	2.16	0.03	0.22	0.22

2.3.1. Conventional TIG and A-TIG welds made with argon shielding

These welds were carried out to provide baseline data on the same cast of austenitic stainless steel to provide comparison with the subsequent trials. Welds were made with argon shielding, both with and without the flux. The parameters used had previously been shown to be optimum for consistent full penetration in 6mm austenitic stainless steel when used with the A-TIG flux (2). The parameters used for these TIG welds made with and without flux were:

Welding travel speed (mm/min): 100

Arc welding current (A): 187

Arc welding voltage (V): Determined by 2mm stand off.

These are the same welds as those presented in Fig. 2. It can be seen that the application of the flux results in a deeper, fully penetrating and narrower weld bead than for conventional TIG welding.

2.3.2. Conventional TIG and A-TIG welds made with helium/argon shielding

Welds were made with the same welding parameters as those made in argon shielding, but using a helium rich shielding gas (75% He/25% Ar) which has a higher ionisation potential than pure argon, thus increasing the arc voltage and, therefore, the overall heat input to the parent material. Welds were made both with and without the A-TIG fluxes. The welds were sectioned and it could be seen that the increased ionisation potential resulting from using the helium rich shielding gas, although producing slightly deeper welds, also produced much wider welds and did not produce welds with a deep narrow morphology in the same way that the fluxes did. It was concluded that the two effects, increased voltage due to the higher ionisation potential of the helium causing a wider weld bead, and increased voltage due to the A-TIG flux causing a deeper molten pool, gave very different results. The use of the fluxes with the helium rich shielding gas produced fully penetrating but much wider welds, and indicated that the two effects were separate and cumulative.

2.3.3. Plasma welds made with the A-TIG flux

High current plasma welding is a higher energy density arc welding process than TIG welding which forms a keyhole during welding to give deep welds. Although the plasma welds made with continuous current were fully penetrating without the fluxes, they showed that the effect of the activated fluxes is not restricted to TIG welds. Whilst welds made with pulsed current were unaffected by the flux, the continuous current plasma welds were affected by the A-TIG flux, reducing the width of the cap of the weld and increasing width of the penetration bead. These results indicated that although the fluxes act to constrict the arc and produce deeper penetration welds, where the arc is constricted by other means, i.e., plasma constriction, the A-TIG flux effect is not as pronounced. They also show that where a deep penetration, keyhole weld pool is disturbed, in this case by low frequency pulsing, the A-TIG fluxes do not have an effect.

2.3.4. CO_2 laser welds made with the A-TIG flux

The laser welds carried out in this programme of work were made to investigate the effect of the A-TIG fluxes on the molten pool without the influence of a current carrying welding arc. The parameters used were designed to produce similar sized welds to TIG welds, i.e. the welds were made with 2.0kW workpiece power at relatively low speeds for laser welding (<1000mm/min) and with the laser de-focused at the workpiece surface. It was determined that the A-TIG fluxes produced increased penetration in these welds and full penetration at a speed of 200mm/min. There was, however, a plasma associated with these CO_2 laser welds and the wider top portion of the laser weld profile is caused by the laser light being scattered by the plasma (14). It was noted that the plasma visibly reduced when the weld moved into the flux coated region. This reduction would reduce the scattering of the laser beam and hence produce a greater power density. The higher density beam could then produce a more depressed molten pool that would cause increased activity, enhanced flow in the weld pool and deeper penetration welds.

2.3.5. Electron beam welds made with the A-TIG flux

Subsequent to the laser welds being made, it was decided to make conduction limited electron beam melt runs with a similar shape to TIG welds. Electron beam was chosen as it produces neither plasma nor an arc during welding. These trials were carried out in order to attempt to separate any effects of arc or plasma constriction and surface tension caused by the flux. Fig. 7 shows a typical conduction limited electron beam melt run with no increase in penetration due to the A-TIG fluxes. However, the results were variable. One weld gave some increase in penetration for the larger of the weld beads made with flux, but this was not observed

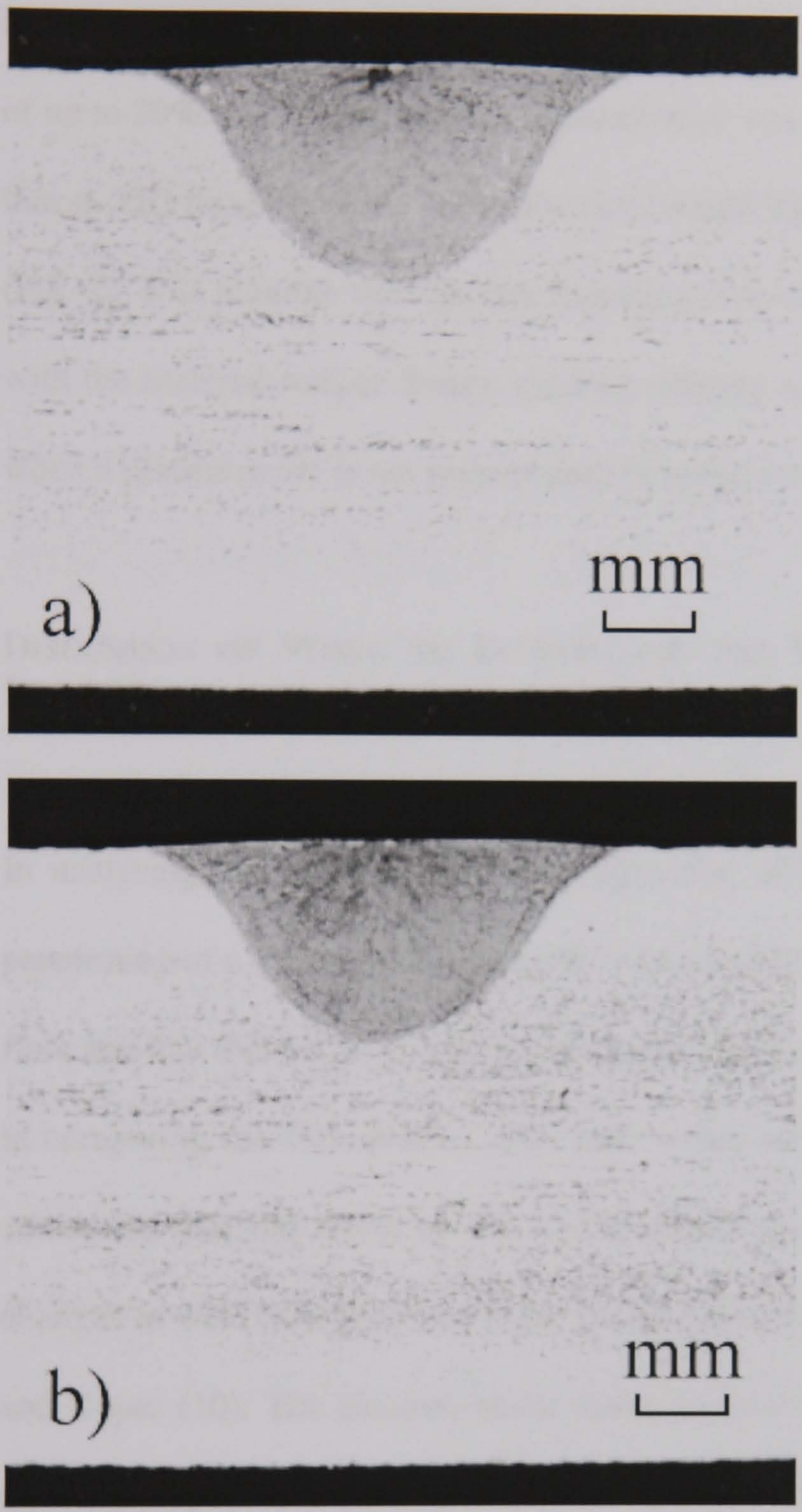

Fig. 7 Macrosections of electron beam welds made at 16.0mA, 6.5kHz on 6mm thickness austenitic stainless steel. Etched in 20% sulphuric acid solution:

a) Without A-TIG flux;
b) With A-TIG flux.

in the other melt runs made and some of the welds showed a reduction in penetration of up to 20%. This slight increase in penetration was not of the same order as the effect that A-TIG fluxes produce on conduction limited TIG welds, doubling the penetration (Fig. 2). It is possible that the flux interferes with the coupling of the electron bream with the material surface during welding, causing some variability in penetration, but when a plasma or arc is not present deep penetration does not occur.

2.4. Discussion of Work to Investigate the Mechanisms for the A-TIG Process

In analysing the results from this programme of work, it was concluded that the penetration of a TIG weld molten pool is determined by both arc effects and weld pool flow and that these effects exist in an equilibrium condition in TIG welding. However, in comparing the TIG, plasma, CO_2 laser welds and the electron beam welds, it was concluded that the effect of the A-TIG fluxes is clearly a very separate effect to changes in weld pool flow due to an altered surface tension effect proposed by Heiple and Roper (10). The electron beam welds particularly showed that when no current carrying plasma or ionised plasma was present above the weld, the deep penetration effect synonymous with A-TIG welding was not present (Fig. 7).

The theoretical explanation proposed by Lucas and Howse (11) suggested an arc constriction effect supported by the fact that this constriction was clearly visible whilst welding. It was concluded that this constriction of the arc led to an increase in current density which in turn led to greater arc forces acting on the molten pool to produce the increase in penetration depth. Other work carried out (1) has also shown that the fluxes reduce the effect of poor weld bead penetration caused by cast to cast variation in stainless steels. As it is widely accepted that Marangoni flow causes cast to cast variability in stainless steels (9, 10, 12), this in itself indicates that the proposed arc effect is a different and dominant mechanism to the Marangoni/surface tension flow effect.

2.5. CONCLUSIONS REGARDING THE A-TIG MECHANISMS

As a result of the work carried out by the author, it was concluded that the arc or plasma is constricted by the action of the A-TIG fluxes and that the associated increase in current density resulted in increased forces which alter the molten pool flow to give increased penetration. Although the fluxes may alter the thermal coefficient of surface tension to give some Marangoni flow in the molten pool, the increased penetration associated with the fluxes is not caused primarily by a change in the thermal coefficient of surface tension.

2.6. SUBSEQUENT WORK ON THE MECHANISMS OF THE A-TIG PROCESS

Work has been ongoing to further investigate the mechanisms responsible for the action of active fluxes (15). This work was supervised by the author and was based upon the author's original findings. The work involved a detailed study of the effectiveness of various different flux constituents in which high speed video footage of the TIG welding arc, both with and without the fluxes, was taken. This work supported and refined the original mechanism proposed in 2.4. It concluded that although the fluxes cause a change in the thermal coefficient of surface tension, this was not the mechanism causing deep penetration in A-TIG welds. The change in flow of the molten pool simply acts to draw the molten surface active flux into the centre of the pool where it acts as a preferential arc current path and produces a smaller anode root than exists for conventional TIG. This increases the current density at the pool surface and alters the balance of electromagnetic or Lorentz forces, generating an axially downward flow in the pool, resulting in increased penetration. Although this work offers a more detailed explanation for the arc constriction and deep penetration caused by the action of the fluxes, it supports the main conclusion of the original work that the primary mechanism for increased penetration with A-TIG fluxes is due to a constriction of the arc rather than a change in the flow of the molten pool.

3. THE REDUCTION OF POROSITY WHEN METAL ACTIVE GAS (MAG) WELDING GALVANNEAL COATED STEEL SHEET USED IN THE AUTOMOTIVE INDUSTRY.

3.1. BACKGROUND

In August 1999, TWI completed a large collaborative programme of work looking at novel techniques for lightweight vehicle manufacture in steel (Liveman). This work involved automotive OEMs (Ford/Jaguar), a primary material manufacture (Corus), Tier 1 suppliers to the automotive industry (GKN and Krupp Camford), welding equipment manufacturers, consumable suppliers and universities. The author was Project Leader for the TWI project (novel joining techniques for lightweight vehicle manufacture in steel) within the Liveman suite of projects, and managed a team of project leaders investigating laser welding, point joining, hybrid joining (point joining with adhesive) and arc welding processes. In addition to managing the Liveman sub-project, the author was responsible for defining, carrying out and reporting the arc welding work. Some of this work was also partly funded by TWIs internal research programme and was reported through this route. It is this work which formed the basis of the second area of research for the Engineering Doctorate looking at novel MAG welding techniques for reducing porosity in galvanneal coated steel sheet.

In the design of lightweight Body in White (BIW) steel structures for the automotive industry, one of the main objectives, in terms of joining processes, is to produce stiffer joint connections than those produced by conventional resistance spot welding (16).

The advantage would be that weight savings could then be derived from a reduction in material gauge using higher strength steel without compromising component strength or stiffness. It is generally considered that a resistance spot welded joint is 20% less stiff than a continuous joint (16). Hence, it is almost inevitable that a continuous process will be employed for a greater proportion of joints in lightweight vehicles.

One large-scale study of lightweight BIW design, using steel, was the Ultra Light Steel Autobody (ULSAB) programme (17). The major objectives of this study were:

- Improved connections at major joints/improved load flow.
- Reduced complexity consistent with structural performance/weight reduction.
- Design for manufacturing and assembly of high volume production in the real world.

All these objectives have clear implications for joining processes. Although the ULSAB project design still required a large percentage of the vehicle structure to be resistance spot welded, for critical areas other processes such as Nd:YAG laser welding, weld bonding and riveting were recommended. However, although these processes are becoming more common amongst the manufacturers of vehicles, suppliers to the automotive industry currently rely heavily upon arc welding as a joining technique to produce sub-component parts, as it is a known and relatively low cost method. In addition, although all of the steels used in the ULSAB design were considered to be weldable, as higher strength, thinner steels are used, the corrosion performance becomes more critical. The margin of safety is less than for thicker materials and all the steels used in lightweight vehicle design are, therefore, likely to be zinc coated in order to improve corrosion resistance (18). In a recent vehicle design, lightweighting was achieved with a steel design in which 48% of the steel used was high tensile steel and 75% was coated (19).

The work carried out by the author and reported here investigated possible solutions for manufacturing components in high strength, thin, zinc galvanneal coated steels using MAG welding techniques to give optimum productivity, reduced distortion and a low defect rate. The lap joint was chosen for investigation as it was this joint that would potentially produce the greatest amount of porosity and hence present the most significant problem for MAG welding of zinc coated steel sheet in the automotive industry. The reduction of porosity, and hence the reduced number of rejected parts during manufacture of sub-components, would significantly reduce the costs and improve the productivity of the process during manufacture.

3.2. REVIEW OF LITERATURE RELATING TO MAG WELDING GALVANNEAL COATED STEELS

Zinc coated steels can be arc welded but they are prone to porosity formation (20). It is acknowledged that the zinc layer becoming vaporised during welding causes blowholes or porosity in galvanised steel sheet welds. The work of Nishikawa (20) has also shown that, for Metal Active Gas (MAG) fusion welding, an increase in welding current and welding speed increases the tendency to form porosity.

However, when welding thinner gauge steels in a production environment, welding at high speed is desirable in terms to increase throughput and reduce heat input and, therefore, reduce the distortion potential of the welding process.

A lap joint traps two layers of zinc coating between the steel. These evaporate into the molten pool during welding, making lap joints highly susceptible to porosity formation (20). Increased welding speed for a lap joint is precisely the condition that most manufacturers within the automotive industry require and as such, the tendency will be for increased porosity formation. Brazing with MAG has been suggested as a solution and produces joints with reduced porosity and reduced distortion by depositing molten material at lower temperatures. However, the process does not fuse the steel base material and the tensile properties of the joint are not suitable for higher strength steel grades (21).

In the full review submitted to the Engineering Doctorate portfolio (22), the author concluded that the development of a procedure for MAG welding zinc coated high strength, thin gauge steels to give a continuous joint would become increasingly important in the development of lightweight structures for the automotive industry. This was due to the increased use of coated steels in automotive body structures and sub-component parts. In order for this to be successfully realised and widely used within industry, the welding process must have the following characteristics:

- It must be readily automated
- It must have reasonable tolerance to poor joint fit-up.

- It must require little or no pre-preparation of the joint prior to welding.
- It must give acceptable joint mechanical properties.
- It should impart as little heat to the parent material as possible to minimise distortion of the welded part and avoid local damage to the zinc coating.
- It must be relatively low cost.

It was concluded that although the MAG welding process was capable of achieving most of these objectives, at the time it was not capable of producing welds giving acceptable joint properties. The largest drawback of the process is the tendency of the zinc coating to evaporate and form pores in the final weld. Although some internal porosity can be tolerated within the joint and still achieve acceptable performance, gross internal porosity will reduce the effective strength of the joint. Surface breaking pores are considered unacceptable and necessitate costly re-work of the joints currently made.

It was also found that a number of techniques have been investigated to reduce porosity in MAG welded zinc coated steels, including increasing the molten pool size, pre-coating the steel with a flux, agitating the weld pool and using brazing techniques (20, 21). However, there was no easily implemented solution available which could be used to achieve low porosity welds in thin gauge, high strength steels used by the automotive industry to produce lightweight vehicles in a high volume production environment.

3.3. Investigation of Novel MAG Welding Techniques for Welding Galvanneal Coated Steel

3.3.1. Experimental Programme

A programme of work was defined to address the problems identified by the literature review (23). A statistical experiment design approach was initially chosen to determine the significant welding parameters to be used to control porosity. Initial trials were carried out to determine the acceptable limits for these parameters using the weld conditions in Table 5.

Table 5 Welding parameters used for statistical experimental design for MAG welding coated steels.

Fixed parameters		**Variable parameters**	
Wire diameter	1.0mm	Welding speed range	0.2 to 1.0 m/min
Welding current	140A	Arc voltage range	17 to 19V
Stand off	20mm	Torch angle	35 to 60°
Leading angle	20°		
Shielding gas	Argon – 5% CO_2		
Gas flow rate	18 *l*/min		
Electrode polarity	DC +ve		

The torch was positioned so that the wire tip was aimed in the corner of the joint where the two faces of the material met (Fig. 8). The welds were made as lap fillets with a 20mm overlap and were tightly clamped to give zero gap between the plates. It was considered that this would be a worst case joint configuration to generate porosity in the welds as it did not allow any route for the zinc vapour to escape except through the molten pool. The plate material was welded as supplied without prior cleaning. After welding, the welds were visually inspected and characterised

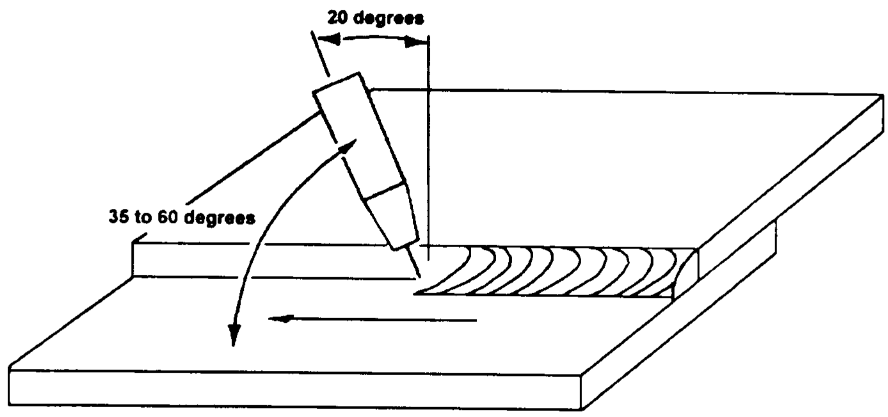

Fig. 8 Positioning of the MAG torch in relation to the lap joints made in galvanneal coated steel.

in terms of the surface breaking porosity and external profile appearance. The first batch of material used was identified as IZ90/Z3 (current grade designation BS EN:10142 DX52D – ZF90) and would not be considered a high strength steel grade. This material had a coating thickness measured on either side of the steel of 7 and 7.5µm. This steel was selected for the initial trials, despite its lower strength, as it was supplied by one of the partners in the project and had a thickness of coating that was known to generate porosity in MAG welds in a production environment. A second coated steel was also used. This was supplied as a high strength, galvanneal coated, interstitial-free steel in the cold reduced condition (typically used by the automotive industry). The material was designated HSIF 305 and does not have an equivalent designation in an appropriate national standard. This material was slightly thinner at 1.8mm thickness and had measured coating thickness of 6 and 6.5µm. The material's chemical analysis and mechanical properties are shown in Tables 6 and 7 respectively.

The statistical experimental design carried out showed very clear relationships between some of the parameters and the porosity generated within the welds. It was decided, after discussion of the results with the Liveman project group, to verify the clearer relationships with a further set of trials made on the same material. Lap welds were again made and radiographic inspection carried out.

Table 6 Chemical composition (wt%) of the material used for MAG welding procedure development for galvannealed steel sheet .

Material	Thick. mm	C	S	P	Si	Mn	Ni	Cr	Ti	Al	B
IZ90/Z3	2.0	<0.005	0.012	0.013	0.008	0.15	0.022	0.016	0.066	0.036	<0.0003
HSIF (305)	1.8	<0.01	0.009	0.047	0.02	1.2	0.02	0.03	0.075	0.035	0.0015
C-Mn (465)	1.8	0.14	<0.002	0.022	0.03	1.24	0.02	0.01	0.058	0.036	<0.0003

Table 7 Mechanical properties of the material used for MAG welding procedure development for galvannealed steel sheet.

Material Designation	Thick. mm	Specified Yield Strength Range Rp 0.2% N/mm^2	Specified Tensile Strength Range N/mm^2	Measured Yield Strength Rp 0.2% N/mm^2	Measured Tensile Strength N/mm^2
IZ90/Z3	2.0	140min to 300max	270min to 420max	174	302
HSIF (305)	1.8	260 min to 290	390min. to 425	305	433
C-Mn (465)	1.8	350min to 400	540min to 565	464	588

Tensile specimens were then produced at the conditions identified as providing a range of porosity values. The intention of this phase of the work was to evaluate the effect of porosity on the tensile performance of the welds. Macrosections were also taken from selected welds.

Finally, a number of trials were carried out on HSIF 305 steel supplied by Corus. This material differed from the original material used to define parameters in that it was higher strength and also had a slightly lower thickness of galvanneal coating. These samples were all de-greased with acetone prior to welding to remove any machining lubricant that was present. Again tensile testing of these specimens was carried out.

3.3.2. Results

On analysing the results from the initial experimental design work, it was concluded that they highlighted important points upon which the remainder of the work should be based. The first was that the generation of large diameter (>1.6mm) surface breaking porosity could not be described by a strong statistically valid relationship. The relationship between any of the parameters and total number of surface breaking pores could at best be described as a trend. Compared to the relationship between the factors studied and the porosity measured from a radiograph i.e., internal porosity, it was a weak relationship. It was concluded, therefore, that it was possible to produce welds giving very low levels of visible surface breaking pores but high levels of internal porosity. This is important in terms of inspection criteria for porosity. If these criteria rely solely upon visual inspection, it is quite possible that welds containing relatively high levels of porosity could easily pass surface examination.

The first batch of tensile testing on the IZ/Z90 steel showed welds with very low internal porosity were still giving poor tensile performance and were not producing strength equivalent to that of the parent material. Subsequently, it was decided to investigate the effect of using alternative shielding gases, and of de-greasing the steel by wiping with acetone, to give better fusion with the parent material and better tensile performance whilst retaining low and acceptable levels of porosity. The results showed that high weld strength (parent material failure) was achieved by cleaning the steel with acetone prior to welding to obtain good fusion at the weld/parent metal interface.

The welds made on the high strength HSIF steel with optimum procedures showed low porosity, and acceptable tensile performance. These results are summarised in Table 8. Weld C11 in Table 8 is a control weld for which the zinc coating was ground off prior to welding to demonstrate the strength of a weld containing very low porosity but made to the same welding procedure.

Table 8 Welds made on 1.8mm HSIF 305 Steel for tensile testing.

Weld ID	Current A	Travel Speed m/min	Voltage V	Heat Input kJ/mm	Surface condition	% Internal Pores of Projected Area	Tensile Strength N/mm^2
C11	150	1.00	16	0.11	Coating removed by grinding	1	399
							409
							401
C1	150	1.00	16	0.11	Cleaned with acetone	3.5	420
							423
							420
C2	150	0.75	16	0.15		2.5	419
							420
							421
C3	150	0.50	16	0.23		2.5	421
							421
							417
C4	150	0.75	19	0.18		17.0	355
							371
							350
C5	150	0.50	19	0.27		1.4	411
							411
							413
C8	200	1.20	18	0.14		6.0 (localised)	415
							415
							375

3.4. Discussion Relating to MAG Welding Galvanneal Coated Steel

The review of literature showed that a reduced level of porosity can be achieved by creating a wide, slow moving molten pool (23). This was explained by the zinc vapour having time to bubble up through the molten pool before it freezes and thus avoiding becoming trapped and forming pores (24). However, the practical experimental design work carried out indicated that at faster speeds and lower voltages, the number of pores formed was also low (Table 8). An explanation for these results is that, as the molten pool is relatively small and will cool quickly, the zinc vapour does not have time to move into the weld pool before it freezes. Certainly, radiographs taken of the low porosity welds indicated that the pores were small and were positioned at the root of the weld which is where they would be expected to initiate. This substantiated the theory that the weld freezes before the zinc vapour bubbles have time to grow and move into the molten pool.

The reported results also showed that repeatable low levels of porosity were achieved at minimum heat input by using a low voltage (17V), low current (150A) or short arc, dip transfer with a travel speed of 1m/min. The speed was not critical in determining the amount of porosity, as all of the low voltage welds made during this work gave low porosity values. Combining this condition with the fastest speed however, gave the lowest heat input resulting in lower distortion in thin sheets.

However, the subsequent tensile testing work using welding conditions optimised for low porosity on the IZ90/Z3 steels also showed that the short arc, dip transfer

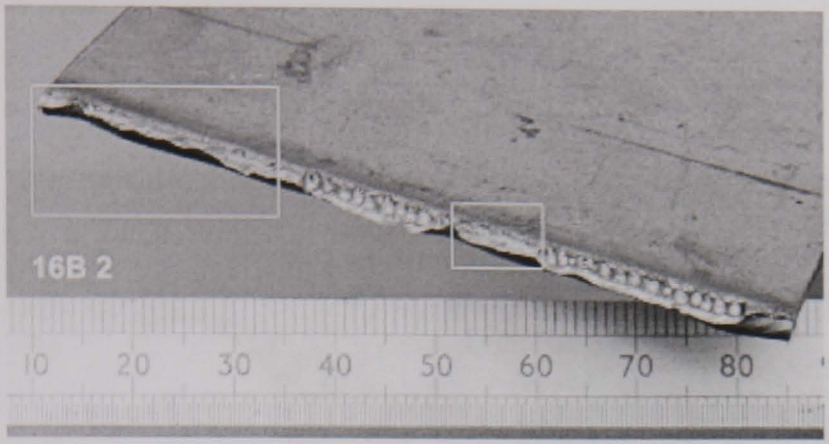

Fig. 9 Tensile test specimen showing weld failure due to high porosity and poor fusion (highlighted).

condition can give poor tensile results. By inspecting the fracture surfaces it was concluded that the welds were failing as a result of lack of penetration of the weld bead Fig. 9. Further work showed that the acceptable tensile performance (parent material failures) was achieved by cleaning the steel with acetone prior to welding. Unlike the welds carried out previously, there was no intermittent lack of fusion with the bottom plate. It was concluded, therefore, that oil present on the steel affected the tensile performance of the weld by causing intermittent poor fusion with the bottom plate. Normally, it would be expected that the intensity of the arc would burn and vaporise any oil on the surface, but in this case the arc is moving relatively quickly and has only a low current. In this case, more care needs to be taken in preparation of the sample prior to welding.

Welds made with a short arc, dip transfer with a travel speed of 1m/min and cleaned with acetone prior to welding, giving similar levels of porosity on the much higher strength HSIF 305 material, gave good tensile results.

It was recommended that for both low levels of porosity and minimum distortion, a low voltage, dip transfer condition at high speed should be used. For acceptable tensile performance to be achieved, cleaning of the steels prior to welding should be carried out.

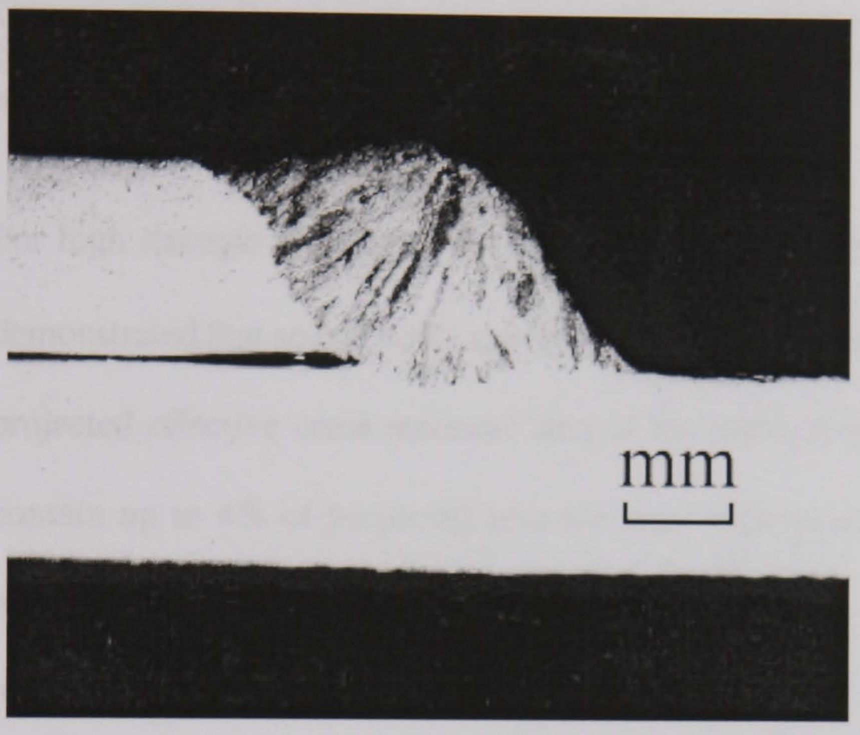

Fig. 10 Macrosection of low voltage, high travel speed condition made on 1.8mm HSIF 305 steel degreased prior to welding. Welding current 150A, arc voltage 16V, travel speed 1.2 m/min. Etched in 2% nital solution.

The industrial partners involved in the project agreed that it was necessary to clean the steels prior to welding to remove lubricating oils introduced as part of the manufacturing process. Although this would introduce another operation to the manufacturing process, it was preferable to the rejection of large numbers of parts due to excessive weld porosity.

As the welds were quite small (although providing adequate throat thickness compared to the material thickness) care should be taken to ensure that the positioning of the welding torch in relation to the joint line is correct along the weld length. Figure 10 shows a macrosection from a low voltage, high travel speed weld correctly positioned to give good fusion with the base material. Again, the industrial partners involved in the project accepted that it was only by adopting more stringent practices for welding these steels that high quality welds could be achieved with low reject rates.

3.5. Conclusions Regarding the Reduction of Porosity when Metal Active Gas (MAG) Welding Galvanneal Coated Steel Sheet used in the Automotive Industry.

For high strength galvannealed sheet with up to 7.5 μm coating thickness, the work demonstrated that sound welds can be made that give levels of porosity of less than 4% projected effective cross sectional area of the weld. It was concluded that welds can contain up to 4% of projected area porosity without adversely affecting the tensile performance. This can be achieved with a low voltage (17V), dip transfer condition made at a high welding speed (1.0m/min). Also, the use of visual inspection to determine whether a weld contains pores is not appropriate. Radiographic inspection should be used to determine the extent of porosity. In order to give acceptable tensile performance, the steel being welded should be cleaned before welding to remove machining oil that can cause lack of fusion defects.

For this particular application, the cost of the welding process itself is relatively small. Using TWIs Weldcost software, the cost of producing a weld with the MAG process at these travel speeds is around 70 pence per metre. The economics of implementation of the process are justified in terms of the reduction in the scrap rate of the welded component part itself. Prior to welding, a typical automotive sub component such as a suspension arm will have to be cut and formed and may also incorporate other machined locating pins and bosses. All the operations which add value to the material costs are carried out before welding and the fabricated cost of the component is, therefore, much greater than the simple welding cost. From discussion with a tier one supplier to the automotive industry the approximate cost of such a component will be in the order of £4.00. However, assuming a reduction in scrap rate of 3% for these components and six units per vehicle, 250,000 vehicles, 1,500,000 components are produced per annum. The cost savings represented by the reduction in scrapped parts will total £180,000 in a year.

4. Nd:YAG LASER WELDING FOR LAND LAY OF PIPELINES

4.1. BACKGROUND

There is considerable emphasis at present on reducing the costs associated with new pipeline development, particularly for large diameter gas transmission lines. Over the next ten years, BP expects to be involved in building over 10,000km of onshore pipelines for transporting oil and gas. Capital expenditure is estimated to exceed $16 billion (25). Over half of the world's undeveloped hydrocarbon reserves are remote from potential users and very large pipelines, up to 1.42m (56") diameter, are required to transport the fuel to market. BP are currently looking at ways to cut costs which has led to implementation of a pipeline cost reduction project. This project is concentrating upon land pipelines and is looking at all aspects of the pipeline process including design, materials acquisition, manufacture and burial of the line and ensuring reliable operation. The welding process used to make the site girth welds has a significant bearing on the total cost per kilometre of pipeline and is one of the areas that BP are investigating as part of their cost reduction project. Current practice is to use either mechanised or automated MAG welding and, in the short term, there may be some cost reduction opportunities offered by incremental improvements to this operation. The multipass MAG welding process, however, requires a high staffing level and the costs of providing this, and the necessary support in fairly remote regions, are a significant component of the overall expenditure.

Despite high capital costs, laser welding, and in particular Nd:YAG laser welding, has now been developed to the stage where it presents opportunities for cost savings, which arise from reductions in labour content. Nd:YAG lasers are now commercially available with power levels of up to 10kW (26). These lasers are particularly suitable for pipe girth welds because the beam is delivered to the workstation through a single optical fibre. Nd:YAG lasers also have a proven production track record in the automotive industry (27). Prior to this project, work at TWI using power levels up to 9kW had demonstrated that deep penetration welds were possible, up to 15mm depth, and that the concept of high power Nd:YAG laser welding of land pipelines is feasible (28). These power levels were achieved by combining the beams from three separate 4kW Nd:YAG lasers. Welding procedures had been developed which produce good quality welds and with satisfactory tolerance to joint fit-up. Additionally, techniques have been developed at TWI during project work led by the author for welding around 360° in the horizontal/vertical position and for the start/stop weld overlap position. A project for BP, aimed at the development and evaluation of the use of Nd:YAG laser welding for new land pipelines, was launched by TWI and CRC Evans in July 2000 (29). The author was involved with the team in setting up this project and was responsible for defining and progressing the experimental work reported here.

The current sequence of manufacture for land lay of large diameter long distance pipelines is for the pipeline to be manufactured by a welding spread comprising a number of individual welding stations, each depositing a single weld pass to make the full weld (Fig. 11). Individual pipe lengths are welded in position with the operations being carried out in the following sequence (30):

i) Pipe facing.

ii) Internal or external MAG root (one station).

iii) Hot pass station (one station)

iii) MAG fill pass stations (six stations).

iv) MAG capping pass stations (three stations).

The above example shows the numbers of individual welding stations that would be used to lay a pipeline with pipe size 1.22m (48") outside diameter and 17mm wall thickness (30). Using this method of manufacture, the effective welding travel speed of the front-end root welding machine determines the maximum pipe lay rate. Developments in arc welding have, therefore, largely concentrated upon making the root pass more efficient and reliable. The speed of the subsequent welding stations has been considered less important as it is possible to simply double up on the subsequent slower filling passes to match the productivity of the root run. This does, however, increase costs. For increasing pipe diameter, root run productivity is maintained by increasing the number of MAG welding heads within the pipe making the root weld (30). The method of manufacture investigated for the BP work was the replacement of the MAG hot pass and fill stations with two Nd:YAG laser welding stations. Two separate laser power sources or a single Nd:YAG laser system with a facility to switch the beam between two fibre optic cables could provide this. Table 9 shows theoretical productivity data for the laser welding

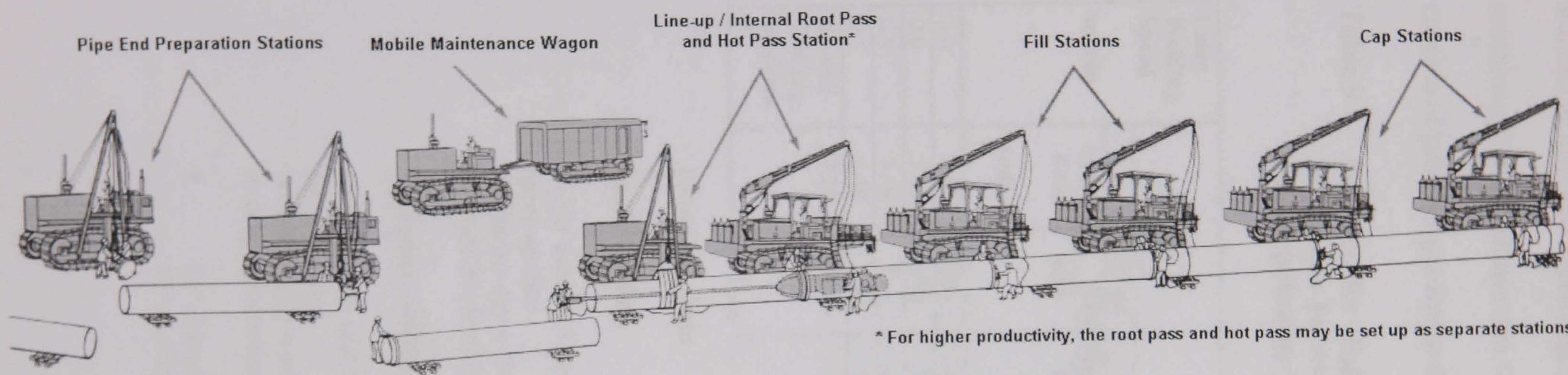

Fig. 11 Pipeline welding spread showing individual welding stations (30).

stations at different speeds against the current productivity of the internal welding machines. Table 9 shows that for all of the pipe sizes considered, the laser must be capable of producing welds at 0.9m/min in order to make welds at the same rate as

Table 9 **Productivity data demonstrating the potential pipe lay rate achievable for two Nd:YAG laser welding stations (Root welding data supplied by CRC Evans).**

Laser Welding Speed m/min	Pipe Diameter m/inches								
	0.91/36			1.07/42			1.22/48		
	cycle time (min.)	Welds/day		cycle time (min.)	Welds/day		cycle time (min.)	Welds/day	
		max.	av.		max.	av.		max.	av.
1.0	4.87	246	172	5.35	224	154	6.83	206	144
0.9	5.19	230	162	5.72	210	146	6.25	192	134
0.8	5.59	214	150	6.19	194	136	6.78	176	122
0.7	6.10	186	138	6.78	176	124	7.47	160	112
Internal Welding Machine *	3.26	184	129	3.1	193	135	3.26	184	129

Formulae used:

Laser welding

Cycle time = (Circumference/travel speed) + 1.0 min set up time + 1.0 min move up time
Welds per day = No. of welding stations (2) x 600min/cycle time
Average production = welds per day x 0.7 efficiency factor.

Root pass welding

Cycle time = (Circumference/ net arc speed) + 1.0 min alignment + 1.0 min move up time
Welds per day = 600min/cycle time
Average production = welds per day x 0.7 efficiency factor.

* 36" diameter pipe 6 weld head internal welding machine
42" and 48" diameter pipe 8 weld head internal welding machine

the internal pipe welding machine. The areas greyed out in Table 9 show where a single laser with a given travel speed operating two fill pass stations will not match the productivity of the internal root welding machine.

Previous work carried out for BP (30, 31) has established that a typical pipeline project is charged at the costs shown in Table 10. This assumes a 1219mm (48") pipeline with 12.54mm wall thickness laid over 500km. These costs are compared with a similar cost for replacing the fill pass arc welding stations with a laser welding process, Table 11. These figures assume for the laser fill option, a 50% increase in consumable parts cost per weld, a 50% reduction in wire cost per weld, reduced number of welding personnel from thirty to fourteen and an increase in the mobilisation cost of £350,000 due to the high capital involved in purchasing lasers.

It can be seen that the implementation of the laser process results in cost saving of around £180,000 for the project equivalent to 8% of the costs of welding the pipeline.

4.2 LITERATURE REVIEW TO INVESTIGATE Nd:YAG LASER WELDING FOR GIRTH WELDING OF PIPELINES

The literature relating to high power laser welding, with particular reference to land lay of pipelines, was reviewed by the author and submitted to the Engineering Doctorate Portfolio (26). This review also investigated existing and near future developments in the field for options relating to commercial availability of high power (>4kW) Nd:YAG laser sources. In addition, equipment and metallurgical

Table 10 MAG welding costs associated with 500km pipelay project

Station	No. of stations	Cost Breakdown		Personnel cost			
				Staff type	**Number**	**Cost per day**	**Staff cost for project**
Root Bead	1	No. of welds	20,000	Lead technician	1	£317.00	£48,769
Hot pass	1	Cost per weld	£27.00	Service technician	6	£317.00	£292,615
First fill	2	Consumable part cost per weld	£9.00	Internal weld op	1	£300.00	£46,154
Second Fill	2	Wire cost per weld	£31.00	External weld ops	22	£127.00	£429,846
Third Fill	2	Lay rate welds per day	130	**Total staff cost**			£817,384
Cap	3	Days to complete pipeline	154				

Total welding cost summary	
Mobilisation fee	£100,000.00
Weld cost	£540,000.00
Consumable cost	£180,000.00
Wire cost	£620,000.00
Staff cost	£817,384.62
Total cost	**£2,257,384.62**

Table 11 **Welding costs associated with 500km pipelay project replacing fill passes with laser welding.**

Station	**No. of stations**	**Cost Breakdown**		**Personnel cost**			
				Staff type	**Number**	**Cost per day**	**Staff cost for project**
Root Bead	1	No. of welds	20,000	Lead technician	1	£317.00	£48,769.23
Laser fill	1	Cost per weld	£27.00	Service technician	4	£317.00	£195,076.92
Cap	3	Consumable part cost per weld	£14.00	Internal weld op	1	£300.00	£46,153.85
		Wire cost per weld	£15.00	External weld ops	6	£127.00	£117,230.77
		Lay rate welds per day	130	Laser weld ops	2	£317.00	£97,538.46
		Days to complete pipeline	154	**Total staff cost**			£504,769.23

Total welding cost summary	
Mobilisation fee	£450,000.00
Weld cost	£540,000.00
Consumable cost	£280,000.00
Wire cost	£300,000.00
Staff cost	£504,769.23
Total cost	**£2,074,769.23**

issues related to the implementation of such laser welding technology were discussed.

In reviewing this literature, it was highlighted that the majority of relevant work which demonstrated the suitability of high power laser welding to structural steels had been carried out using CO_2 laser welding. The beam quality of CO_2 lasers, which affects the power intensity of the focused spot, was better than that currently available with the Nd:YAG lasers used to make welds at higher powers. The Nd:YAG laser would, therefore, have a larger focused spot size and produce wider welds. Because of this, for welds made with equivalent power at the workpiece and giving similar penetration, the travel speed will be slower and the heat input will be greater with Nd:YAG than for CO_2 laser welds (26). Therefore, Nd:YAG laser welding results in a slower cooling rate of the fused zone and reduced hardness compared to CO_2 laser welding for equivalent laser powers.

Pipeline steels are generally leaner composition/lower carbon equivalent value (CEV) than structural steels and are, therefore, less hardenable with lower strength. It was concluded that, for high power Nd:YAG laser welding of pipeline steels, fracture path deviation would be much less

of a cause for concern than for CO_2 laser welding of higher CEV structural steels.

A change in weld morphology and cooling time could also adversely affect both susceptibility to solidification cracking and the final microstructure of the weldfused zone, giving poor impact toughness properties. Weld metal solidification cracking can be a particular problem for laser welds made at high speed. It is associated with the formation of low ductility, highly segregated regions during welding which remain liquid to low temperatures during solidification and can be pulled apart as the weld metal contracts (32). Susceptibility to solidification cracking is related to a number of factors such as travel speed, weld bead shape, parent material composition and thickness, joint fit-up and joint design (33). It was not possible to predict what the extent of cracking would be in high power Nd:YAG laser welds made at speeds of 1.0 m/min in low carbon content pipeline steels as the chemical composition, bead shape and cooling rate are all different to the data generated from other work (33). In terms of microstructure, as the cooling rate is slower than for CO_2 laser welding, it is expected that coarser and softer microstructures will be generated possessing lower toughness.

Generally speaking, all autogenous single pass welding procedures generate coarse microstructures with inherent poor toughness (34). If finer microstructures can be generated by fast cooling, weld filler additions or refinement by heat treatment, toughness can be improved. However, a positive aspect is that the poorer beam quality, lower processing speeds and wider welds produced with the Nd:YAG laser mean that the process will be more able to bridge gaps and give greater tolerance to variation in joint fit up.

The literature review also concluded that steels with a more suitable composition for laser welding have been developed which could be made available as pipeline products in the long term (26). Use of these steels would generate fine grained microstructures during autogenous laser welding, giving welds with acceptable toughness. It was recommended that welding of these steels should be investigated as part of any ongoing project work.

It was also recommended that consideration should be given to the robustness of any procedures developed. The process developed must be capable of producing positional welds in variable environments with variation in joint fit up. For pipe welding there are often variable gaps in the joint which the process must be capable of bridging. Similarly, as the pipes themselves are not perfectly round, there will potentially be vertical misalignment in places around the circumference of the weld preparation. Seam tracking will need to be employed and the tolerances of the manipulation equipment used to make the welds will have to be considered in terms of the operating windows of the procedures developed. Laser welds tend to produce much narrower welds than for conventional arc welding techniques (32) and the risk of missed edges or lack of side wall fusion defects is increased. However, as commercial seam tracking systems for lasers are currently available and integrated with existing manipulation systems for lasers, this should not present a significant problem.

The use of hybrid laser/arc processes was also considered. Hybrid laser/arc welding combines a laser with an arc welding process in the same molten metal pool (35). Where filler wire is also introduced, as is the case for laser/MAG welding, the technique can offer a number of advantages over either of the two processes used in isolation. It was concluded that the use of hybrid Nd:YAG laser/MAG welding techniques, although further complicating the welding process, would offer a relatively simple method of boosting the input energy, thereby possibly increasing welding travel speed. In addition, introducing a filler material would result in modified fused zone composition, improved toughness, better resistance to solidification cracking and increased tolerance variation in joint fit-up.

4.3 EXPERIMENTAL WORK TO INVESTIGATE Nd:YAG LASER WELDING FOR GIRTH WELDING OF PIPELINES

In parallel with the review of the literature, an initial practical study was carried out to evaluate Nd:YAG laser welding at 8.2kW of power delivered to the workpiece for pipeline welding (36). The aim of the work was to carry out initial trials for fill pass welding of a multi-process joint. The joint consisted of a MAG internal root run, an Nd:YAG autogenous laser fill, and a MAG capping pass made in the joint preparation shown in Fig. 12. The intention was to make Nd:YAG laser fill passes in samples that had been prepared by CRC Evans which represented typical pipe welding joint fit-ups. These samples were used to assess the performance of the laser welding process in terms of tolerance to

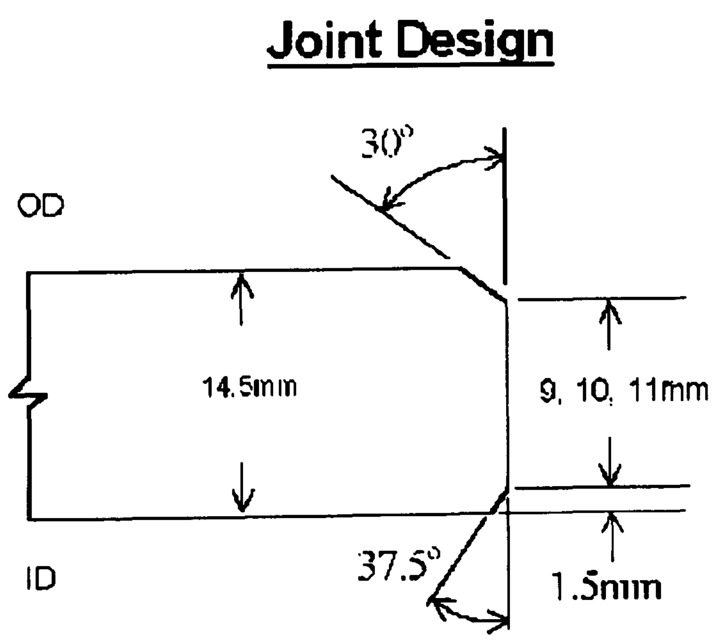

Fig. 12 Joint preparation used to evaluate the laser welding of pipe sections of 914mm pipe OD.

joint fit-up, productivity and also provide some initial joint mechanical property data. An example of a completed weld is shown in Fig. 13.

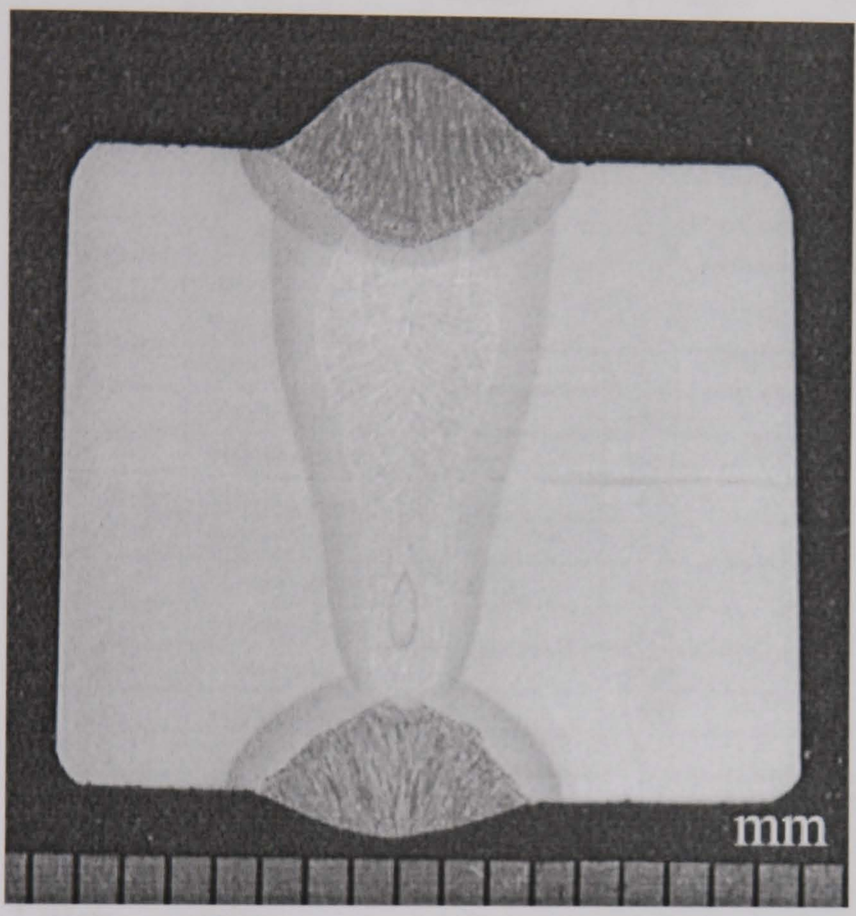

Fig. 13 Macrosection of completed weld showing laser welded fill on 10mm root face made at 8.2kW laser power at the workpiece, 0.8 m/min travel speed –4.0mm focus position and MAG internal root and external capping pass. Etched in 2% nital solution.

Twenty-six welds were made varying welding parameters to establish optimum processing conditions in terms of achieving penetration at the required processing speed of around 1.0m/min (Table 12). Selected welds were then visually and radiographically examined and used for metallographic analysis, hardness testing and Charpy impact testing. These results were used to determine the process' suitability for pipeline applications and to define areas for further work.

These welds were carried out on API 5l grade X70 linepipe material manufactured by Ipsco with 914mm (36") outside diameter and 14.23mm (9/16") wall thickness. The chemical composition for this steel is shown in Table 13.

Table 12 Welds made with 8.2kW laser power at the workpiece.

Weld	Joint	Travel Speed (m/min)	Focus Position relative to workpiece (mm)	Surface Condition	Gas Shield (l/min)
W1	BOP	1.0	0	As received	jet 20
W2	BOP	1.0	-2.0	Ground	jet 20
W3	BOP	1.0	-2.0	Ground	jet 10
W4	BOP	1.0	-2.0	Ground	Co-ax30/ jet 20
W5	9mm face	1.0	-2.0	As received	Co-ax 30/ jet 20
W6	BOP	1.0	-4.0	Ground	Co-ax 30/ jet 20
W7	9mm face	0.8	-4.0	As received	Co-ax 30/ jet 20
W8	10mm face	0.8	-4.0	As received	Co-ax 30/ jet 20
W9	10mm face	0.8	-4.0	As received	Co-ax 50/ jet 20
W10	9mm face	1.0	-4.0	As received	Shoe 50/ jet 20
W11	10mm face	0.8	-4.0	As received	Co-ax 50/ jet 20
W12	11mm face	0.7	-4.0	As received	Co-ax 50/ jet 20
W13	11mm face	0.7	-4.0	As received	Co-ax 50/ jet 20
W14	10mm face	0.8	-4.0	As received	Shoe 50/ jet 20
W15	9mm face	1.0	-4.0	As received	Shoe 50/ jet 20
W16	10mm face	0.8	-4.0	As received	Shoe 50/ jet 20
W17	BOP	1.0	-4.0	As received	Shoe 50/ jet 20
W18	BOP	1.0	-4.0	As received	Shoe 50/ jet 20
W19	BOP	1.0	-4.0	As received	Shoe 50/ jet 20
W20	BOP	1.0	-4.0	As received	Shoe 50/ jet 20
W21	11mm face	0.7	-4.0	u prep	Shoe 50/jet 20
W22	11mm face	0.7	-4.0	u prep	Shoe 50/jet 20
W23	11mm face	0.7	-4.0	u prep	Shoe 50/jet 20
W24	10mm face	0.8	-4.0	u prep	Shoe 50/ jet 20
W25	9mm face	1.0	-4.0	u prep	Shoe 50/ jet 20
W26	9mm face	1.0	-4.0	u prep	Shoe 50/ jet 20

BOP: bead on plate weld

Jet: angled plasma control jet

Co-ax: co-axial shielding

Shoe: trailing shoe used for shielding

Table 13 Chemical composition (wt%) of IPSCO linepipe material supplied by CRC Evans for Nd:YAG laser welding trials (TWI report number: S/00/238 and O/N/00/65)

C	Mn	P	S	Cr	Mo	Ni	Al	As
0.04	1.58	0.010	0.003	0.11	0.21	0.17	0.028	0.011
B	**Co**	**Cu**	**Nb**	**Ti**	**V**	**O**	**N**	
<0.0003	0.010	0.30	0.066	0.022	0.003	0.0021	0.0096	

It was noted that there was some variation in the welds made on the samples provided. The partly welded samples were supplied by CRC Evans to their standard tolerances and contained variable joint fit up from zero gap to around 0.5mm. One sample was, therefore, welded for which the joint gap had been measured and showed a steadily increasing gap from one end to the other prior to welding. This sample showed a visible deterioration in weld quality along its length once the joint gap was greater than 0.2mm. Radiography of this weld showed that internal defects, not detectable on visual inspection, started to occur at around 0.1mm gap. A photograph of this weld is shown in Fig. 14. It was clear that the fit-up was critical and that the larger gaps present in some samples could not be tolerated by autogenous Nd:YAG laser welding at these processing speeds.

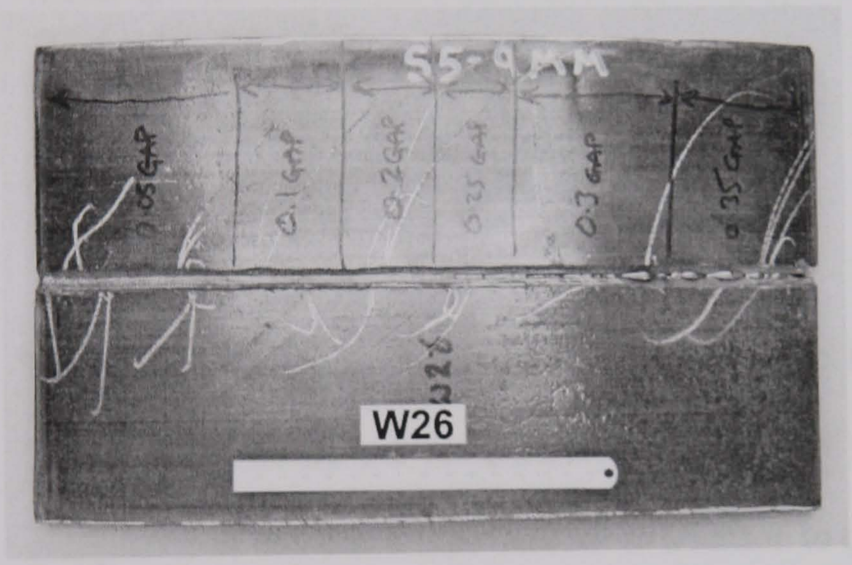

Fig. 14 Nd:YAG laser weld made on a sample with ground U preparation and 9.0mm root face. The sample was welded with 8.2kW power at the workpiece, 1.0m/min welding speed, -4.0mm focus position. This shows the effect of increasing joint gap and deterioration starts at approximately 0.25mm gap.

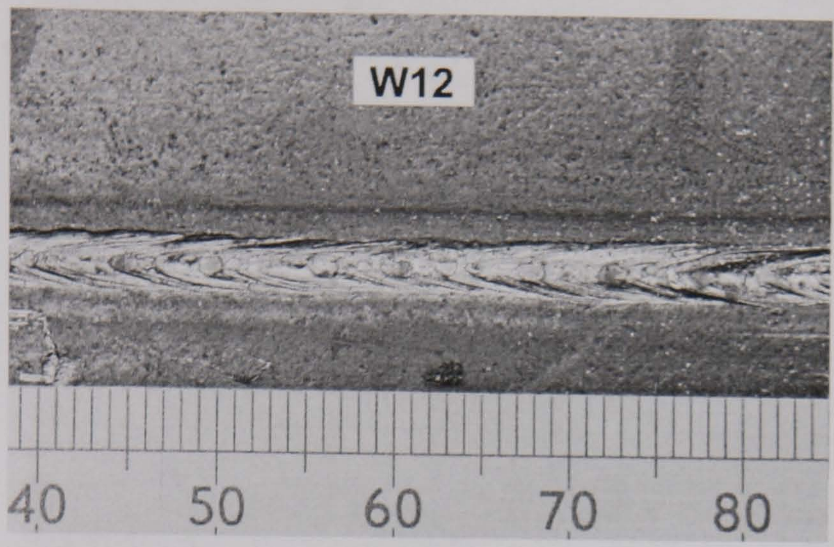

Fig. 15 Laser weld, 11.0mm root face, 0.7m/min travel speed, -4.0mm focus position. Showing typical good surface quality.

Where the gaps were less than 0.2mm welds all showed acceptable results in terms of visual appearance and internal porosity. Internal porosity was within limits defined by BS 4515: 2000, Welding of steel pipelines on land and offshore.

All of the twenty six welds made exhibited some form of solidification cracking. These welds would not be acceptable in terms of BS4515, which does not allow acceptance of any crack type defects. In addition to the solidification cracking, some inter-run lack of fusion defects were also noted which again would not be acceptable to BS 4515. Examples of the achievable surface quality, microstructure and solidification cracking can be seen from the images presented in Figs. 15, 16 and 17.

Figure 15 shows the top surface of a laser weld made in an 11.0mm root face preparation. The surface is relatively smooth and even and could easily be capped with a final MAG welding pass.

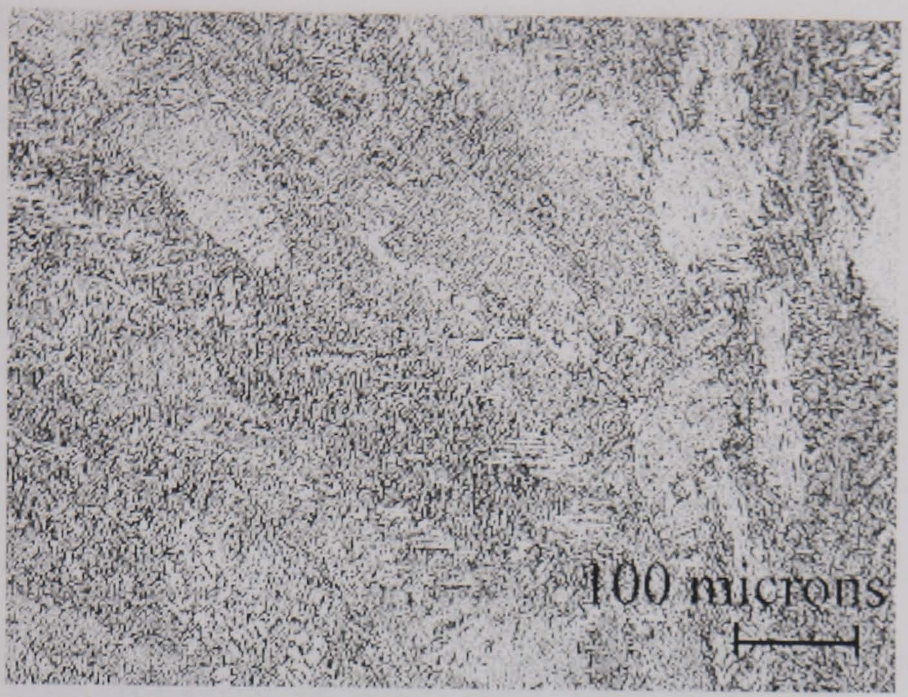

Fig. 16 Typical high power Nd:YAG laser fused zone weld microstructure showing coarse ferrite columnar grains with aligned second phase. Etched in 5% nital solution.

Hardness testing of selected samples showed that the maximum hardness of the fused zone ranged between 241 and 298HV5 compared to the parent material hardness of between 231 and 248HV5. Hardness overmatch was, therefore, relatively low. The metallographic analysis of the weld and heat affected zones showed that the grain structure in the weld metal was coarse, with finer grain structures being seen in the heat affected zone (HAZ). A typical micrograph of the weld metal is shown in Fig. 16.

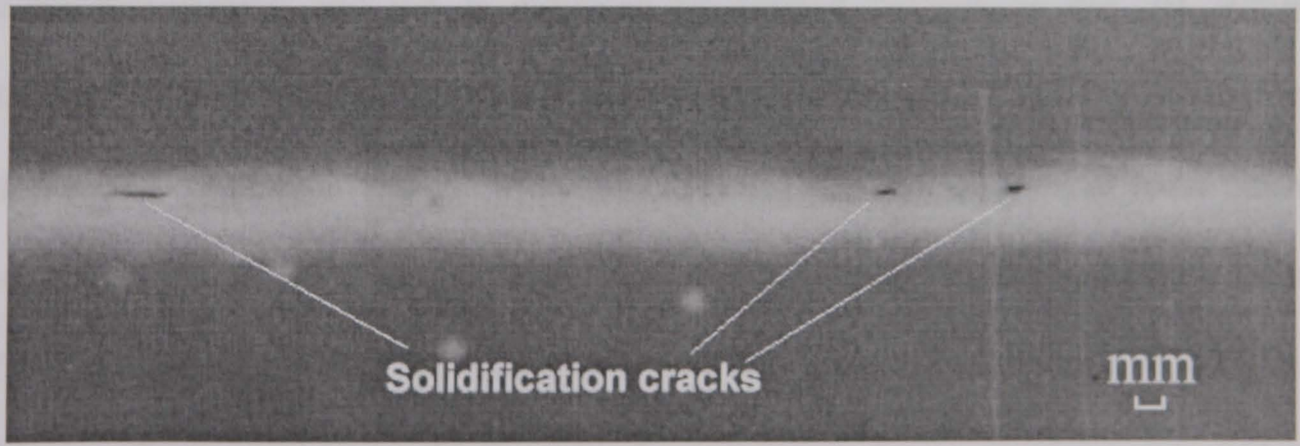

Fig. 17 Detail from radiograph of laser fill weld, 11.0mm root face, 0.7m/min travel speed, -4.0mm focus position, showing centre line solidification cracking in the weld metal.

Figures 17 and 18 show typical solidification cracks, both from a radiographic image and in cross section. Typically, these defects are only a few millimetres in

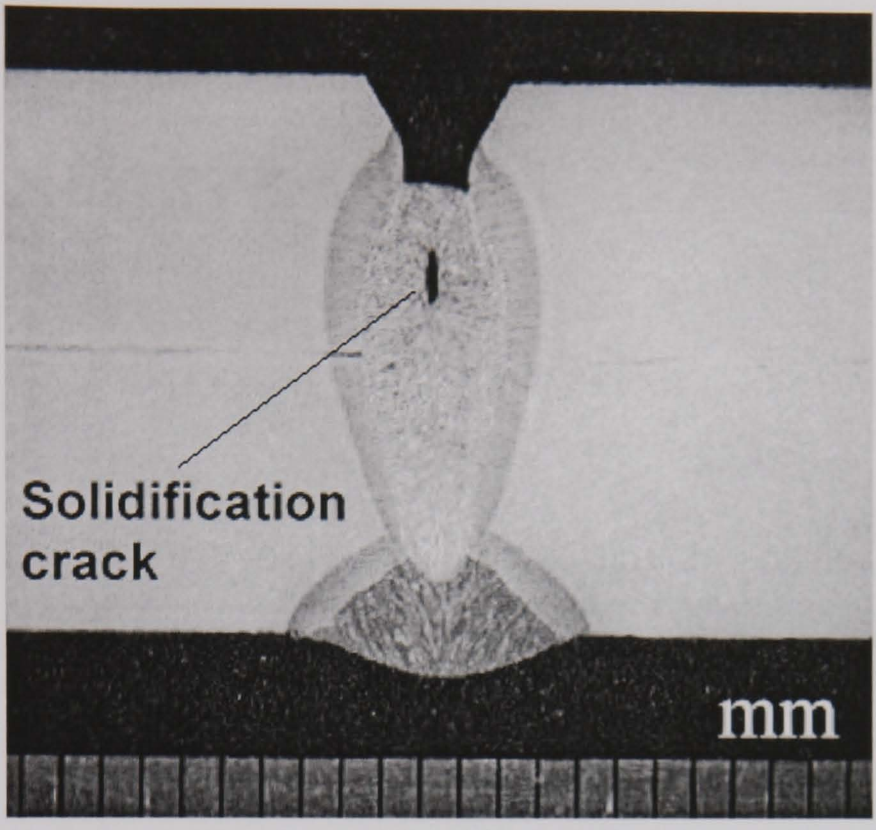

Fig. 18 Macrosection of weld made at 8.2kW workpiece power, 9.0mm root face, 0.8m/min travel speed, -4.0mm focus position, showing typical solidification defect. Etched in 2% nital solution.

length and depth and occur in the centre of the weld. It was noted that these defects were usually associated with a bulge in the weld. Figure 18 shows such a defect.

As discussed above, all of the welds made showed some form of solidification cracking. Charpy data was obtained for these welds and these are summarised in Fig. 19. As expected, many of the fracture surfaces of specimens notched at the weld centreline contained defects, and this is indicated by crossed symbols in Fig. 19. Whilst toughness specifications for pipeline girth welds vary from country to country depending on climate and the individual national standards, a typical requirement would be 35J at –10°C. It should be noted that the Charpy impact specimens taken from the welds were 7.5mm sub size specimens as the penetration was not quite 10mm. The transition toughness value has, therefore been extrapolated to 26J to compare to 35J for full size (10mm samples). This was not met by the welds tested during this investigation. The best results achieved by these welds were 26J transition temperatures at 10°C. Specimens notched in the parent metal and HAZ

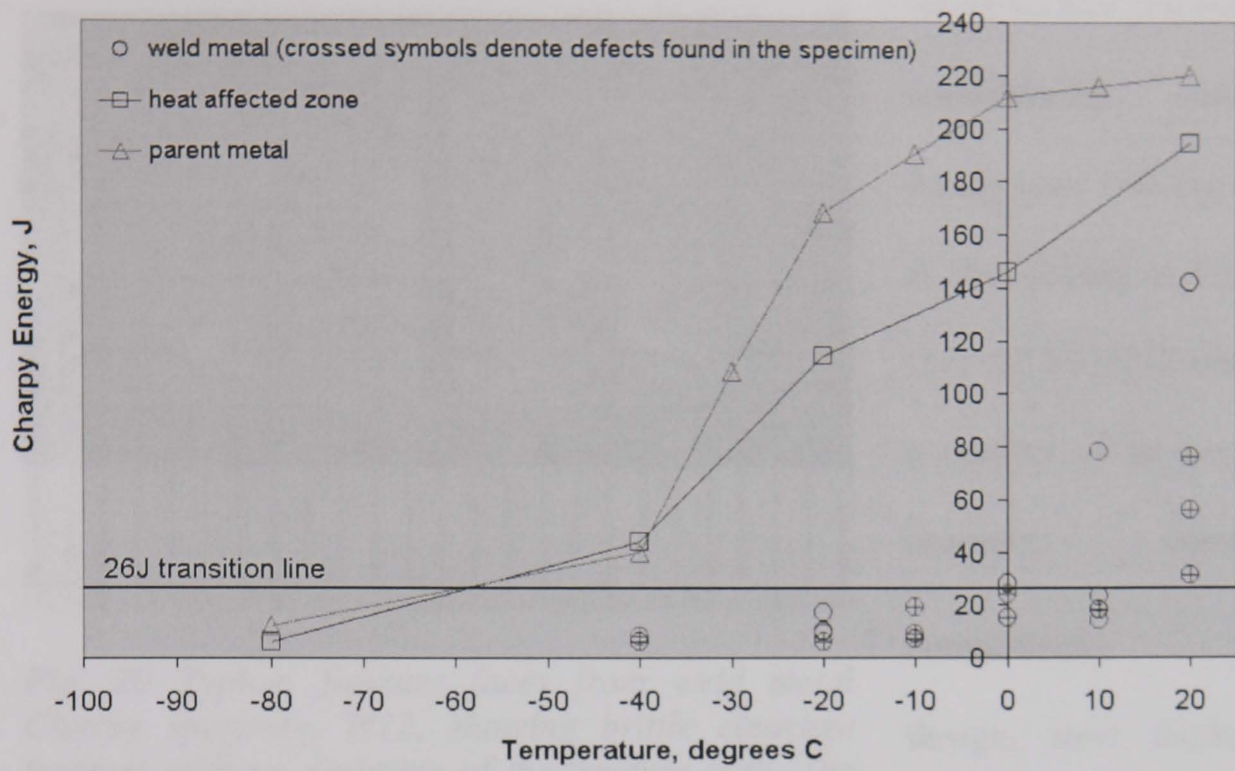

Fig. 19 Charpy impact transition data for Nd:YAG laser welds.

showed much higher Charpy energy than those notched at the weld centreline, with a 26J transition temperatures below -40°C for both sets of results.

4.4 DISCUSSION RELATING TO Nd:YAG LASER WELDING FOR GIRTH WELDING OF PIPELINES

4.4.1 Solidification Cracking

In terms of the quality of the laser welds produced within this work and their practical application to pipewelding, the extent of solidification cracking is one of the major obstacles that must be overcome if the technique is to be successfully implemented.

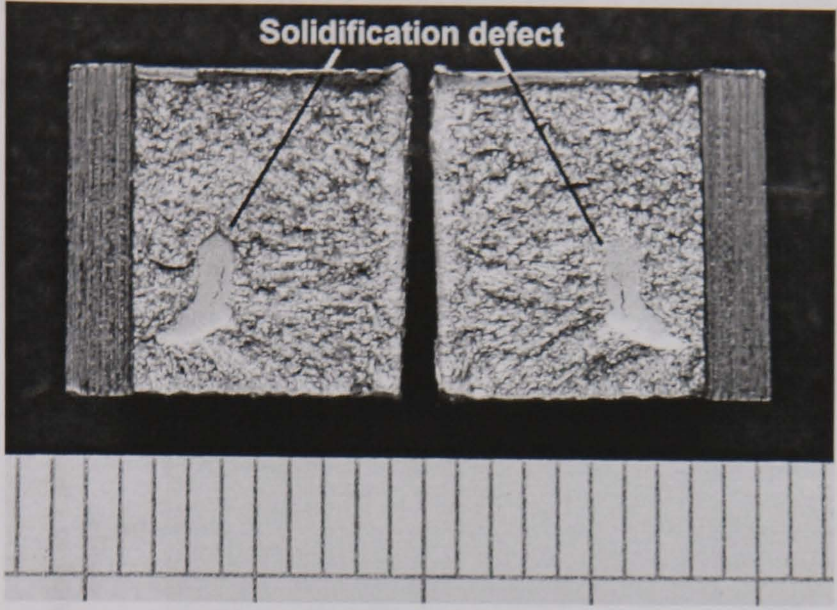

Fig. 20 Typical fracture faces from weld metal Charpy specimen, W12, showing brittle cleavage fracture with no deviation of the fracture path. The specimen also shows a typical centreline solidification defect.

As mentioned previously, solidification cracking during laser welding such as that shown in Fig. 20 (32) can be influenced by a number of factors, for example, chemical composition, joint design, steel thickness, welding travel speed and weld shape. For pipeline manufacture, the material thickness, and to a large extent the joint design and chemical composition, is fixed. Reduction in the welding speed could give positive benefits in reducing solidification cracking, but the speed must be maintained at around 1.0 m/min in order for the process to remain economically viable. Previous work has also shown that high levels of sulphur and phosphorus can promote cracking, as can both very high and very low levels of carbon (32, 37). The composition of the steel tested here has relatively low levels of carbon, sulphur and phosphorus although this would be typical for pipeline steels (Table 10).

The weld bead shape, and hence the tendency to form solidification cracks is influenced by beam focus position (33). The percentage length of solidification defect, plotted against welding speed and focus is shown in Figs. 21 and 22 respectively. It can be seen that although the travel speed has an effect, with both higher and lower travel speeds giving a reduced susceptibility, the focal position also contributes. This is in line with similar experience of solidification cracking

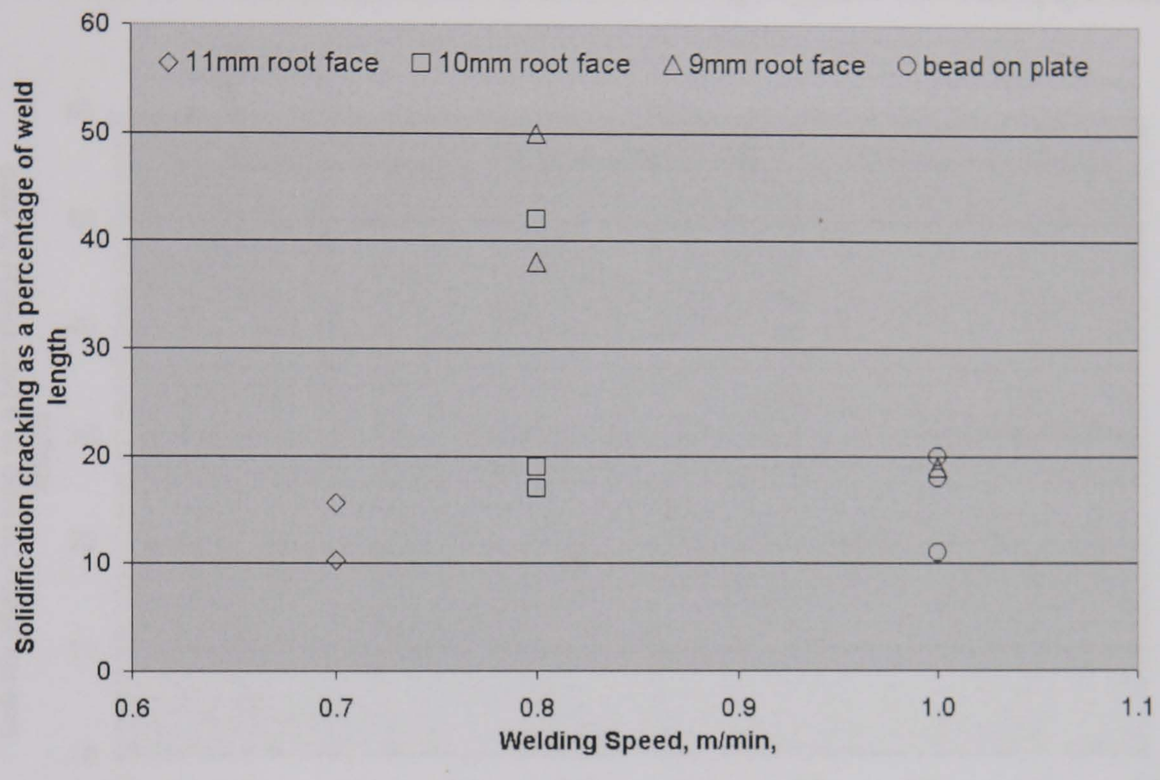

Fig. 21 Effect of welding travel speed on percentage solidification cracking.

while using CO_2 lasers (37, 33). The further the focal position is placed into the plate material, the higher the risk of cracking as the thicker bulging welds produced are more prone to cracking defects (33). This suggests that positive benefits could be achieved by adjusting the focal position in further trials. However, focal position will also affect the depth of penetration and there will be a trade off between optimum focal position to achieve adequate penetration and optimum focal position for reduction of solidification defects. There is some scope for increasing speed in the 9.0mm welds on samples containing very good fit-up. For the 11.0mm root face samples, which require a slower speed at this laser power for full penetration and are, therefore, less susceptible to cracking, adjustment of the focal position could change the weld bead shape to become more parallel sided and eliminate solidification cracking.

The steel tested in this programme of work, although typical for a linepipe steel, had

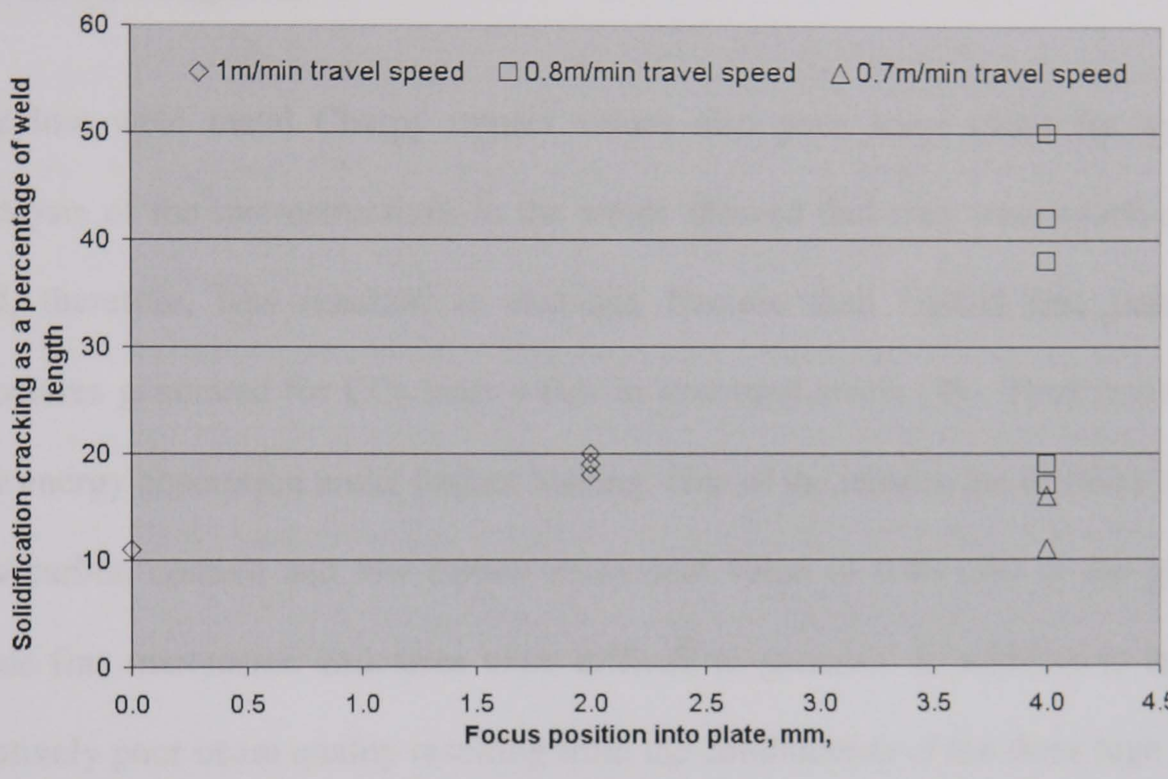

Fig. 22 Effect of focus position on percentage of solidification cracking.

a relatively low carbon level when compared to structural steels used for other work investigating solidification cracking (33, 37). It has been noted (37) that lower carbon levels in steels can promote the incidence of cracking due to a wider freezing range. Given that these low carbon levels are typical in pipeline steels, there is little scope for suggesting compositional changes to the parent material that will give good resistance to cracking that can be practically implemented in the short term. However, it is recommended that other compositions of steel be investigated as this could provide a solution in the longer term, provided that it does not adversely affect any other of the required properties. Unfortunately, any restriction on composition imposed by the operators would attract a premium cost for supply by the steel producers, which could outweigh any economic advantages through increased productivity.

.2 Weld Metal Toughness

The low weld metal Charpy impact values also gave some cause for concern. Analysis of the microstructures in the welds showed that they were much coarser and, therefore, less resistant to cleavage fracture than typical fine martensite structures generated for CO_2 laser welds in structural steels (38). Thus resulting in low energy absorption under impact loading. One of the reasons for this was that the low carbon content and low carbon equivalent value of 0.40 (39) of the pipeline made fine martensitic structures more difficult to generate. In addition to this, the relatively poor beam quality resulting from the combination of the three high power Nd:YAG lasers producing a larger focused spot size (1.4mm diameter), gave wider welds than are usually seen for CO_2 laser welds made with equivalent power levels. This variation in weld width also affected the cooling rate producing longer cooling times in these welds (40). The combination of all these effects means that it will not be possible to increase cooling rate to generate finer and tougher microstructures by optimising the weld procedure through changing existing procedure parameters because the cooling times are too long. However, for sufficiently tough microstructures to be developed in pipe welds made by high power Nd:YAG welding there are two further options.

i) Control of steel composition.

Work has been carried out to investigate the effect of steel composition on toughness for autogenous laser welds (41, 42). Restricting the amount of aluminium and adding boron or titanium additions alters the autogenous weld metal structure of these steels. This produces a fine grained acicular ferrite structure, typical of that seen for conventional welding processes made with a consumable filler and higher weld metal oxygen content (41, 42). Again, although trials demonstrating this approach have only been carried out on CO_2 laser welds, the same principle will give acicular ferrite microstructures and increased toughness in autogenous high power Nd:YAG laser welds (43).

ii) Addition of oxygen to the molten pool.

The second option for producing a tough, fine-grained, acicular ferrite microstructure would be to alter the ratio of Al/O to less than or equal to unity by adding oxygen to the molten pool by combining the process with a filler addition. This has been demonstrated to produce the required microstructure in arc welds (34).

3 Hybrid Laser/Arc Processes

For a more robust welding system capable of coping with the accepted fit-up tolerance currently used for arc welding, a wire feed technique could be used to fill gaps and produce acceptable welds. For a cold wire feed system, i.e. a system where there is no electrical energy passed through the consumable wire, the energy used in melting the filler wire would further reduce welding speed to an extent whereby the process would no longer be economical. However, hybrid laser/MAG welding would introduce molten filler and additional heat energy into the pool and would boost the performance of the welding process, increasing either penetrating capability or welding speed (35). If a consumable wire was introduced, it would also present the opportunity of adjusting weld pool chemistry and produce a microstructure less susceptible to solidification cracking and giving better weld metal toughness.

It was, therefore, recommended that in order to produce pipeline girth welds with an 8.0kW Nd:YAG laser at speeds of around 1.0 m/min, which will give resistance to solidification cracking and acceptable weld metal toughness for joints containing gaps up to 0.5mm, hybrid Nd:YAG laser/MAG welding should be investigated.

Conclusions Regarding the Use of High Power Nd:YAG Laser Welding for the Production of Large Diameter, Long Distance Land Pipelines

The work carried out here showed that it was possible to achieve a fully fused 9.0mm root face at a welding speed of 0.8 m/min with 8.2 kW Nd:YAG laser power suitable for an autogenous laser fill procedure in pipeline steels by optimising focal position. The welds made within this programme of work also demonstrated that acceptance criteria for maximum hardness in the weld metal of 275HV for non sour service could be met. However, all of the welds showed some degree of solidification cracking which would fail to meet acceptance for pipeline applications. Also, the weld metal toughness acceptance criteria for pipe girth welds operating in sub zero environments was not met. The microstructures generated in the weld metal were coarse ferrite with aligned second phase giving low hardness (maximum 271HV) and poor impact toughness (26J transition temperatures at 10°C).

The current levels of joint fit-up tolerance for arc welding, up to 0.5mm joint gap, will be too large for autogenous Nd:YAG laser welds operating at speeds of approximately 1.0 m/min. It was, therefore, recommended that the use of a high power Nd:YAG laser in combination with a MAG welding system should be investigated. This would give increased resistance to solidification cracking, increased weld metal toughness and greater tolerance to joint fit up variation. This approach will also give increased processing speed.

It was also recommended that the possibility of using novel steel compositions promoting the formation of tougher weld metal microstructures, and giving resistance to solidification cracking, should be investigated.

4.6 SUBSEQUENT WORK TO INVESTIGATE Nd:YAG LASER WELDING FOR GIRTH WELDING OF PIPELINES

As a result of the work reported here, subsequent work carried out at TWI (supervised by the author) has concentrated upon investigating methods of improving toughness in Nd:YAG laser welds in pipeline steels and combining the process with MAG welding to reduce the incidence of defects and further improve productivity.

This author's initial work had highlighted the need to produce tough acicular ferrite microstructures in the fused zone through either controlling the composition of the pipeline steel or adding a consumable filler wire.

In order to investigate the first of these recommendations, a laboratory cast sample of steel (obtained by the author) with a composition intended to generate tough acicular ferrite microstructure was used to make an autogenous Nd:YAG laser weld (44). The weld microstructure was assessed and Charpy impact testing was carried out. The microstructure formed was predominantly acicular ferrite and sub size Charpy impact tests, used to sample the weld metal only, gave extrapolated 35J transition temperatures of $-40^{o}C$. This is well within the customer requirements of 35 J transition at $-10^{o}C$.

However, although these results were encouraging, the option whereby the laser is combined with a consumable filler is preferred, as the process eventually adopted will have to cope with a range of commercially available linepipe products, i.e., with varying compositions.

Work has therefore been carried out to investigate the hybrid approach. A consumable filler wire was added by combining both Nd:YAG laser and MAG welding. By adopting this approach, the weld metal toughness has been improved to give 60J at –10°C, well in excess of the 26J requirement at –10°C for sub size Charpy samples. The tolerance to variation in joint fit up has also been increased and the potential to form internal flaws such as solidification cracks can be eliminated, although at the expense of weld penetration (45).

In addition, the added power input of the MAG process has increased the welding travel speed. Results have shown that by combining the MAG process with a 3kW Nd:YAG laser, fully penetrating welds of around 7mm depth are possible at 1.0m/min travel speed. Samples have also been produced using this combination in the flat, vertical up and 45° overhead position showing acceptable penetration and cap profiles (45).

More recent work that the author has participated in has demonstrated that with 8.9kW of Nd:YAG laser power at the workpiece combined with MAG welding used in a machined edge preparation, weld depths of up to 14mm can be achieved at speeds of 1.0m/min (43). Although these welds contained some solidification defects, wider welds with 10mm depth have been made without solidification defects. The parameters used to produce these welds were also used to produce fully welded pipe butt samples in the vertical down position on 762mm (30") outside diameter pipe (43).

Although there is still further work to be carried out in refining hybrid Nd:YAG laser/MAG weld procedures for girth welding pipelines, these results have shown that it is possible to meet toughness and productivity targets whilst reducing solidification cracking. These results have also validated the recommendations made from the author's initial work.

5 OVERALL CONCLUSIONS

Although the theme of improved productivity in fusion welding is potentially very wide in its scope, the three main themes reported here, comprising the work for the EngD, all demonstrate improved productivity through a greater understanding of the welding processes or by novel application of existing fusion processes.

The work carried out here has extended the existing knowledge and practice in the field within each of the three themes by either reducing defects or by making welds in a more efficient and economical manner.

5.1 THE USE OF ACTIVE FLUXES FOR TUNGSTEN INERT GAS (TIG) WELDING

The work was carried out to determine the fundamental mechanisms at work with the A-TIG process and contributed to a greater understanding of the process. The practical work was designed to establish the dominant mechanism producing deep penetration A-TIG welds. It was concluded that:

- The increased penetration associated with the use of activating fluxes was shown not to be caused by a change in the thermal coefficient of surface tension (Marangoni flow).

- The arc or plasma is constricted by the action of the fluxes and the associated increase in current density results in increased forces which alter the molten pool flow to give the observed increase in penetration.

5.2 THE REDUCTION OF POROSITY WHEN METAL ACTIVE GAS (MAG) WELDING GALVANNEAL COATED STEEL SHEET USED IN THE AUTOMOTIVE INDUSTRY

This work was carried out to provide a solution to an existing manufacturing problem in the automotive industry, i.e., that of poor quality arc welds in zinc coated high strength steel sheet. Using a statistical experimental design approach, robust, high productivity, low heat input welding procedures were designed that could be applied to solve the problem with existing MAG welding technology in an industrial environment. It was concluded that:

- For high strength galvannealed sheet with up to 7.5 μm coating thickness, sound welds can be made that give levels of porosity of less than 4% projected effective cross sectional area of the weld. This can be achieved with a low voltage (17V), dip transfer condition made at a high welding speed (1.0m/min).

- In order to give acceptable tensile strength, the steel being welded should be cleaned before welding to remove machining oil that can cause lack of fusion defects.

- As the weld bead is relatively small, the precision with which the welds are applied should be carefully considered, as for any high quality welding process.

- Welds can contain up to 4% of projected area porosity without having the tensile strength adversely affected.

- The relationship between the number of internal pores and those that are surface breaking is extremely weak. It cannot be assumed that welds with no surface breaking porosity contain only small amounts of internal porosity. Radiographic inspection should be used to determine the extent of porosity.

5.3 THE USE OF HIGH POWER Nd:YAG LASER WELDING FOR THE PRODUCTION OF LARGE DIAMETER, LONG DISTANCE LAND PIPELINES

The work carried out on this theme investigated the replacement of conventional arc welding process by a laser welding process to produce a step change in the productivity. Although the lifetime of the full project extends beyond the author's registration on the Engineering Doctorate programme, the initial work carried out by the author and reported here demonstrated that the process is technically feasible and is capable of producing significant cost reduction. Specific conclusions were:

- Examination of weldments produced using only laser welding indicated that all of the welds exhibited solidification cracking which would fail to meet acceptance for pipeline applications. Solidification cracking must be eliminated if the process is to gain industrial and regulatory acceptance and practical implementation.

- High power Nd:YAG lasers, with relatively large focused spot sizes compared to CO_2 lasers, are not capable of producing acceptable welds in parts with fit-up tolerances suitable for arc welding of up to 0.5mm at the welding speeds investigated.

- The fused zone produced by welding pipeline steels with autogenous Nd:YAG lasers has low toughness.

- Both focus position and welding travel speed affected the shape of the weld bead and hence the tendency towards solidification cracking. Lower welding speeds and a focal position at the steel surface tended to reduce cracking.

- Novel steel compositions promoting the formation of tougher weld metal microstructures and giving resistance to solidification cracking have been proved to be effective in producing tough fused zones with autogenous Nd:YAG laser welds. This is achieved by the control of the Al/O_2 ratio and addition of Ti and B in the steel promoting the formation of acicular ferrite.

- The autogenous Nd:YAG laser welds made within this programme of work would meet acceptance criteria for maximum hardness in the weld metal of 275HV and in the heat affected zone of 350 HV.

- The use of a high power Nd:YAG laser in combination with a MAG welding system has been shown to give increased resistance to solidification cracking, increased weld metal toughness and greater tolerance to joint fit up variation at 1.0 m/min welding speed.

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APPENDIX 1

LIST OF PUBLICATIONS

The following is a list of papers that have been published from this work to date:

Howse, D.S. and Lucas, W., "An investigation into arc constriction by active fluxes for TIG (A-TIG) welding", *Science and Technology of Joining and Welding*, (5), **3**, 2000, pp. 189-193.

Howse, D.S., "Avoiding porosity when MAG welding of high strength coated steels", Seminar, Galvanised Steel Sheet Forum – Automotive, 15-16 May 2000, Institute of Materials, London UK.

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