COLLABORATIVE WELDING RESEARCH IN AUSTRALIA LEADING TO THE DEVELOPMENT AND APPLICATION OF WELDING TECHNOLOGY FOR IMPROVED PRODUCTIVITY IN GAS TRANSMISSION PIPELINE CONSTRUCTION AND ALUMINIUM SHIPBUILDING

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Abstract : *As part of a comprehensive program of welding research and technology development under the auspices of the Cooperative Research Centre for Materials Welding and Joining in Australia over the past 7 years, significant effort has been devoted to reducing the costs of welding-related pipeline construction activities including:*

- *early release of the internal line-up clamp;*
- *lifting and lowering-off while root pass welding is being completed;*
- *use of high strength cellulose electrodes for root welding of API 5L X70 and X80 grade pipe;*
- *rationalisation of the defect acceptance criteria for flaws in girth welds in thin-walled pipe.*

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INTRODUCTION

Long distance pipelines in Australia for the transmission of natural gas from source to market are invariably constructed from relatively small diameter (typically 12" to 18" diameter) and relatively thin-walled (typically 6 to 10 mm thick) ERW welded high strength steel (X65, X70 and X80) pipe. The terrain over which the majority of these pipelines are constructed is flat and featureless, so that construction rates of at least 240 joints per day are expected, which progresses the pipeline by 4 to 5 kilometers per day. The flexural behavior of 18 m lengths of these pipe sizes is one of the main reasons why judicious placement of just 50% of the root pass has been shown to be safe practice prior to release of the internal clamp. Early lifting and lowering-off onto styles releases the side-boom to move to the next pipe length, while the front-end team completes welding of the root pass. By the time the welders and technical support personnel with their equipment reach the next girth weld, the joint is aligned and the root gap is set ready for the welders to proceed. The construction rate has been accelerated by a factor of 1.5 over the prior art, resulting in substantial construction cost savings and early completions and commissioning. A fracture mechanics study of the significance of weld imperfections has shown the importance of at least matching the weld metal strength to that of the pipe material, and the research has developed a software package called "PIPE-SAFE" for risk assessment to the Australian Pipeline Code. Friction stir welding (FSW) presented an opportunity to efficiently butt join 6 mm thick marine grade AA5083-H321 plates using a single-pass, one-sided, complete-penetration technique, so as to preserve the plate properties in the near-weld joint region. This was a paramount requirement for the construction of the upper bow section of a prototype 24 m long ocean-viewer vessel, since the bow shape was to be explosively-formed to net shape prior to fabrication of the bow plates onto the vessel. The

FSW process was developed at the TWI-Abington, but the process had not been industrially applied prior to this aluminium shipbuilding trial. Portable welding equipment was developed and tested in the research laboratories of The University of Adelaide prior to shipping to the construction site near Cairns in North Queensland. A total of 6 joints were successfully made in the bow sections, while another 6 m of weld joints were made in the forward decking. The completed joints passed all of the quality acceptance tests imposed by the marine surveyors and the root side of the explosively-formed joints only required light sanding to finish the unpainted bow section.

COOPERATIVE WELDING RESEARCH IN AUSTRALIA

The mission of the CRC for Materials Welding & Joining (CRC-MWJ) was "to achieve the effective application of new and improved welding and joining processes, primarily for metallic materials." This mission was vigorously pursued through targeted tactical and strategic collaborative research, via technology demonstration and information dissemination, and through welding education initiatives. The main aim was to enhance the competitiveness of Australian industry by fostering the adoption of new technologies developed by the CRC and of best practice technologies from elsewhere identified through the Centre's international linkages.

At the commencement of the CRC-MWJ in July 1992, the research program was structured to address specific topics which were considered to be both industrially relevant, and which could best be undertaken using the resources and expertise residing within the collaborative partners. The research providers were particularly responsive to the technological needs identified by BHP-Steel (one of the core partners) in conjunction with the WTIA Technical Panels. Most of the projects undertaken had a 3-year horizon, and the majority of the projects involved post-graduate students receiving scholarships from the CRC-MWJ. At the end of 1995, the CRC-MWJ was subjected to a performance review.

The main outcomes of this external review were:

- the initial portfolio of research projects had been brought to a successful completion;
- CRC-MWJ post-graduates were being eagerly recruited by Australian industry;
- a Welding Industry Technology Needs Study had been undertaken to assist the CRC-MWJ Management Team with refocusing of the next round of research projects;
- internationally-accredited Graduate Diploma and Masters level course-work programs were in place at the Universities of Adelaide and Wollongong;
- the first Graduate Diploma graduates were feeding back into Australian industry to take up key positions in welding coordination.

During the first half of 1996, restructuring of the Centre's research program was done to align the research activities to industry sectors. The Australian pipeline industry became a key participant in the CRC-MWJ, contributing $300,000 p.a. cash support and matching in-kind to underpin a targeted sub-program of tactical and strategic research directly addressing the needs of the pipeline industry. The CRC-MWJ sought to establish similar collaborations with other industry sectors including:

- aluminium and steel shipbuilding;
- automotive and automotive parts;
- welding equipment;
- power generation / mining / structural fabrication.

The Research Program was considered to be very successful in terms of the large number of research students who had already completed or were in the final stages of their Masters or Ph.D. programs. A total of 6 PhD's and 6 ME's were completed, while another 21 students were well advanced in their respective research activities. The success of the CRC-MWJ Education Program was readily measurable by the healthy participation rate and the demand for access to the coursework programs at the respective Universities, with a total of 23 graduates, 5 of whom had successfully achieved European Welding Engineer (EWE) accreditation. In order to provide improved access to the coursework program by students across Australia, as well as by international students, planning to introduce a distance-learning program was put in place. The CRC-MWJ Technology Transfer Program had been catalytic in establishing international linkages with key overseas organisations, including the TWI in the UK, the Universities of Osaka, Ghent, Cambridge, Cranfield and Bradford, the Colorado School of Mines, Harbin Welding Research Institute in China, and the Paton Welding Institute in Ukraine. The appointment of State Technology Managers as part of WTIA's Technology Support Centres Network Program was a crucial element in the linking of the CRC-MWJ research, education and technology transfer activities with Australian industry.

MAIN RESEARCH ACHIEVEMENTS OF THE CRC FOR MATERIALS WELDING & JOINING

Hollow bead defect control in pipeline girth welds

Hollow bead occurs unpredictably in the root pass of girth welds in line pipe, and its presence causes very costly interruptions to the normal pipeline construction routine, resulting in costly delays and costly repairs.

Disputation between pipeline owners, constructors, pipe suppliers and welding electrode suppliers is inevitable when this problem arises. Under the auspices of the WTIA/ Australian Pipeline Industry Association Panel 7, the pipeline industry sought the assistance of the CRC-MWJ to investigate the causes and remedies of hollow bead defect formation.

A comprehensive study of the occurrence of hollow bead defects in pipeline girth welds has resulted in a complete understanding of the mechanism of its formation, and the identification of the operating conditions which control its formation. Although other factors have some influence, the use of high welding currents combined with fast welding speeds were shown to be the main contributors to the onset of the defect.

Potential savings in Australia based upon elimination of hollow bead are conservatively estimated at $50,000 per 100 kilometers of pipeline constructed.

Mechanised welding of small diameter thin-walled pipelines in high strength steels

Pipeline welding in Australia is normally conducted manually using cellulose electrodes, whereas larger diameter, thicker-walled pipe is more efficiently welded using automated processes. With the trend to the increased use of higher strength steels for thin-walled small diameter pipelines in Australia, a project to develop efficient mechanised welding systems was commenced in July 1996. One of the main issues was the rate of joint completion using the automated process in comparison to current practice, since pipeline constructors will not adopt slower alternatives, despite technological advantages being identified. The researchers at the University of Wollongong have reviewed the international developments in mechanised girth welding systems and the most suitable commercially-available technology was evaluated in laboratory trials. The progress to date has generated considerable industrial interest, and the successful implementation of the developed welding and in-process quality control system will impact very positively on reducing the construction cost of future pipelines. The combination of using higher strength pipe and mechanised welding is projected to save about 10% of pipeline construction costs in Australia, which is estimated to be about $1B over the next 5 years.

High current TIG welding of Aluminium

High current TIG welding is a process that enables deep penetrating weld runs to be made along the seam of tightly-butted plates, so as to efficiently join them without the use of added filler metal. The process has been further developed and commercialised as an integral part of the CRC-MWJ Research and Technology Transfer Programs over the last 6 years, and is now impacting on the national and international stage. World-wide interest in this efficient single-pass complete-penetration welding process is such, that licensing of the technology will provide the CRC with a significant income stream.

Service behaviour of welded marine grade Aluminium Plate

Fatigue cracking in ocean-going passenger and freight aluminium catamarans and in the superstructure of naval vessels is a significant problem. The CRC-MWJ has co-sponsored projects on assessing the effect of weld treatments on fatigue performance of welded butt joints. The development of mechanised welding of small throat-thickness fillet welds as a means of achieving improved weld profiles to reduce stress concentration factors associated with abrupt weld toes and poor weld metal/parent metal transitions was also investigated. The developed technology not only substantially improved the fatigue performance, but it also enabled the reduction of the overall cost of the original fabrication by eliminating over-welding, which can add dead-weight amounting to about 6 tonne to a typical completed vessel. The cost saving is estimated to be $0.6M per vessel.

Intelligent Welding Power Sources

Modern welding power supplies for gas shielded metal arc welding have control systems which diagnose the operating conditions and incorporate feed-back controls to maintain a stable metal transfer condition. The University of Wollongong has worked closely with an Australian welding equipment manufacturer to develop improved control hardware to optimise arc stability, metal transfer, fume generation and spatter formation characteristics. The incorporation of the improved technology in welding power sources is projected to provide the CRC with royalty income amounting to at least $100,000 p.a.

Joining of Aluminium-based MMC's for Automotive Parts

The manufacture of high performance transmission drive shafts from aluminium-based metal matrix composites for export to a US automotive manufacturer has prompted an evaluation of solid-state joining technologies to replace conventional arc welding processes. Friction and MIAB (magnetically impelled arc butt) welding have been investigated for butt joining of tubular sections to forged end fittings. Pre-production welding trials have been done in conjunction with Kuka GmbH in Augsburg, with students at the University of Adelaide assisting with the metallurgical characterisation of the welded prototypes.

Remnant Life prediction of thermal plant in the Power Generation Industry

The power generation industry sector has been a long-term supporter of research activity to develop improved methods for accurately assessing the through life performance of elevated temperature plant. Conventional analysis methods rely on uniaxial creep rupture data, whereas such plant is subjected to complex multiaxial stresses combined with cyclic loading, which results in a significant discrepancy between predicted and actual life. The significance of this research lies in the need for informed decision-making on either in-service maintenance or replacement of key components in the power generation industry. The cost of making an ill-informed decision which results in an unscheduled shut-down or a catastrophic failure is significant, and the CRC-MWJ research is aimed at avoiding such occurrences.

R&D IN CONSTRUCTION OF GAS TRANSMISSION PIPELINES

Over the past 20 years, the Australian Pipeline Industry has achieved significant economic improvements in the design and construction of natural gas transmission pipeline networks. This improvement is based on the use of thin walled high strength high pressure pipelines which serve relatively small markets separated by long distances from gas reserves. Australia is a vast continent, Fig.1, comprising 7.6 million square kilometres with a relatively small and dispersed population of 18 million. Demand for natural gas is about 20% of primary energy requirements, which is attributed to the relative young age of the gas industry and also the remote location of principal markets to major reserves. Principal markets are mainly the state capital cities, serviced from separate sedimentary basins through long transmission pipelines. These are small in diameter, and for economic reasons, they are thin-walled and operated at high pressure. As natural gas is now Australia's fastest growing energy source, demand is estimated to double over the next two decades [1], and is further underpinned by the versatile combustible qualities of gas and most importantly, its environmental friendliness when compared with coal. To meet the anticipated increase in demand, it is imperative that new transmission pipelines are constructed in a timely and cost effective manner. Fig 1 shows the proliferation of pipelines across Australia.

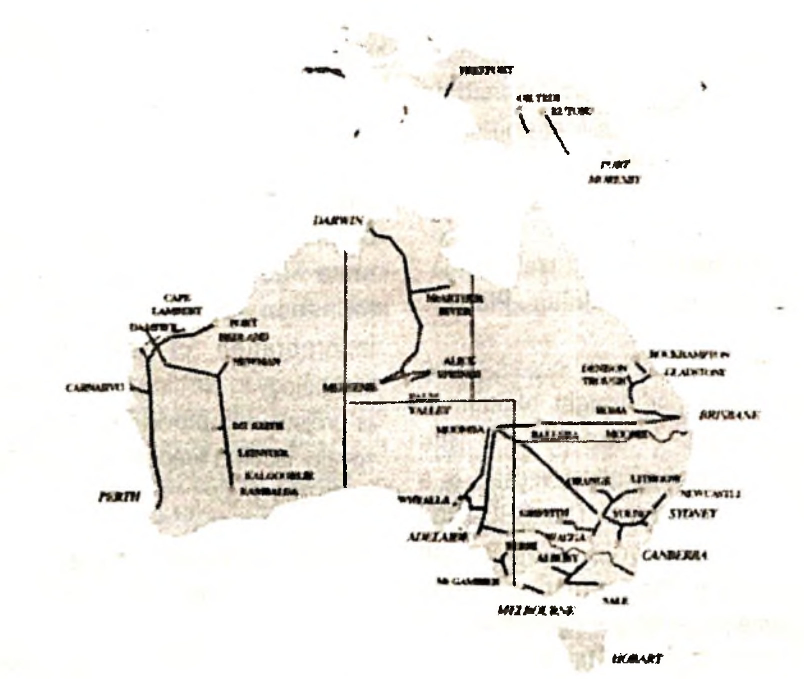

Fig. 1 : The Australian pipeline network

Defect acceptance levels in girth welds

The Australian Pipeline Code AS2885 1995, Part 2 - Welding now incorporates a three tier approach for assessment of girth weld defects. This code contains a workmanship based level (Tier 1) similar to that of API 1104, and a provision for an Engineering Critical Assessment (Tier 3). The principal change is the introduction of an additional Tier 2, which is a fitness-for-purpose approach based upon the European Pipeline Research Guidelines (EPRG). However, the EPRG guidelines [2] do not extend below a wall thickness of 7 mm and pipe grades greater than API 5L X65 and therefore do not fully address the Australian scene, where thin wall and high strength pipe is commonly used. The research therefore aimed to establish girth weld defect acceptance limits in thin walled, high strength linepipe. The approach was to extend the EPRG gross section yielding criteria down to 5mm wall thickness and pipe grades up to and including X80 with the use of conventional cellulose electrodes using wide plate tests and artificial defects.

The specific aims of the project were to determine :

- defect acceptance levels in high strength X70 and X80 pipe;
- weld metal consumable strength matching capabilities;
- maximum defect depth for thin wall pipeline girth welds;
- influence of welding variables, eg., high/low, reinforcement height.

The experimental approach involved the assessment of different welding electrodes in 5 mm thick X70 and 5 & 8.6 mm thick X80 grade pipe with the view to assessing the capability of cellulose electrodes in the fabrication of API 5L X80 grade pipe. The fracture toughness of both cellulose and the E91T8 flux cored arc welding electrodes was shown to satisfy the EPRG Tier 3 requirements, specified for pipe grades up to X65, to avoid brittle fracture [3]. However, the use of the E9010 electrodes in X80 grade pipe was shown to be incapable of providing yield strength matching. The E91T8 exhibited strength matching in X80 pipe. In relation to pipe yield strength, it was demonstrated that an E6010/E9010 combination could not match the strength of X70 grade pipe at the upper end of the expected strength range. Overmatching of weld metal yield strength with respect to pipe yield strength ensures gross section yielding (GSY) where displacement controlled loading occurs. This was shown to be valid for pipe wall thickness down to 5 mm and grades up to X80, which is consistent with the philosophy adopted by the EPRG.

Field Welding Limits

The aims of the research were to investigate the stresses induced in pipeline girth welds during welding and lifting of the pipeline and the effect of the field welding practices used during the construction of transmission pipelines on the propensity for the generation and propagation of cracks in and adjacent to girth welds. Field conditions in Australia for welding pipelines are frequently less onerous than those of the countries where the traditional limitations on welding practices originated. In particular, very low temperatures are less relevant and terrain is frequently flat or gently undulating. Further, Australian pipelines are predominantly of moderate to small diameter and use high strength steels which results in wall thickness below 10mm. This makes the root pass a much larger proportion of total thickness with a correspondingly reduced cooling rate.

Australian experience with one major pipeline has shown that 16 inch API 5L X 70 pipe with a wall thickness of 9.5mm can be welded with clamp release at 70% root pass completion, and with lifting and lowering-off being completed while root pass welding was in progress.

The particular field welding conditions which were investigated include:

- The extent and location of partial welding of the root pass before clamp release, lifting and lowering-off;
- Pipe lifting and lowering-off practices;
- Weld pass location in relation to applied stresses.

All experiments were performed outdoors by experienced pipeline welders using typical pipeline welding equipment (clamps, supports, welding generators, consumables, lifting equipment) and welding conditions (ambient temperature, joint preparation and condition). In addition, sufficient lengths of pipe were used so that the pipe string was representative of full-scale conditions. Typically, 3 to 4 lengths of pipe were used. The pipe sizes and grades are shown in Table 1. Linear displacement transducers and strain gauges were used to measure weld shrinkage and lifting stresses. The measuring devices were designed such that they would not interfere with the welding and handling practices, and such that they could also be used during the construction of an actual pipeline. The initial part of the experiments concentrated on studying the factors which would promote cracking in the weld. These factors were the location of segments of the root pass with respect to top and bottom dead centre (TDC and BDC) and the percentage of completion of the root pass before the removal of the internal line-up clamp and lifting. The lifting stresses are dependent on the percentage of root pass completion and the location of the start of the welds with respect to TDC. The latter

Table 1 : Specification of linepipe used in the experiments

Material Grade (API 5L)	X60		X70		X80	
Diameter (mm)	219.1	219.1	355.6	406.4	406.4	457
Wall Thickness(mm)	8.1	5.7	7.6	8.8	7.8	8.6

being a function of the section modulus which affects the bending moment and therefore bending stresses. Smart and Bilston [4] found a starting point of 20^0 after TDC with a 50% completion of the root pass resulted in a higher stress condition during lifting, and that a lower stress condition was a starting point of 20^0 before TDC. These two conditions were used in the experiments. Two lift heights were considered, 300 and 600 mm corresponding to a normal and an extreme condition respectively. The X60 pipe with a wall thickness of 5.7 mm was welded using 3.2 mm diameter E6010. The electrodes used in all other experiments were 4.0 mm diameter E6010.

An essential component of this research was the validation of the data obtained from the simulation experiments by conducting similar experiments during the construction of a pipeline in Central Queensland. The linepipe was grade API 5L X70 with an outside diameter of 323.9mm and a wall thickness of 6.9mm. The internal line-up clamp was removed after 70% root pass completion. The lifting operation was almost simultaneous with the removal of the clamp. The lift height at the free end was between 200 and 300mm from the top of the stiles. The measured displacements at the TDC were always lower than those at BDC. The displacements when converted to strains (over 5mm weld thickness) showed that the weld metal undergoes plastic deformation. No cracking was found after welding even when the root pass was allowed to cool without the hot pass being deposited. The displacements measured due to lifting increased with increasing diameter and thickness. There was only a slight increase in the displacements when the lift height was increased from 300 to 600mm. The strains (over 5mm weld width) put the weld in the plastic range, but these strains were completely removed once the pipe was lowered. No cracking was detected after lowering-off, even though the lifts in the simulation experiments were carried out when the weld had been cooler than in field experiments. There appears to be no cause for concern about root bead cracking when E6010 electrodes are used for root pass welding. It was also found that for all pipe grades and sizes the stresses above yield occur only in a small region at the end of the weld segments (for 50% root pass completion). The remainder of the weld experiences stresses well below yield. This result correlated well with finite element model predictions.

Weld Metal Cracking

A feature of Australian gas pipeline construction is the high productivity and cost-effectiveness arising in part from the use of cellulose electrodes for root pass welding, without preheat. Australian produced ERW pipeline grades up to 9 mm thickness in X70 and up to 12 mm in lower strength grades have been successfully girth welded using cellulose electrodes and an extension of established procedures to thin-walled X80 pipelines has been generally considered by the industry to be a desirable and achievable goal. Strength matching considerations, however, demand E9010 or higher strength electrodes, raising concerns about the danger of hydrogen assisted cold cracking (HACC) in the weld metal.

The research work was done to :

- elucidate the factors responsible for HACC in the weld metal of X80 pipeline steel;
- develop guidelines for safe welding procedures for field girth welding of X80 pipeline steels using cellulose electrodes.

The project plan to enable these objectives to be met consists of :

- the adoption of the Welding Institute of Canada (WIC) test as a laboratory simulation of root pass girth welding;
- the conduct of a comprehensive WIC testing program for 8.6 mm X80 steel strip using three commercially available E9010 consumables; and
- property and structural characterisation of both all weld test pieces of the consumables and their X80-diluted weld metals.

According to Graville [5] the WIC test approximates the restraint and bending stresses occurring across the weld face at the 6 o'clock position during field root pass welding and lifting. Given appropriate calibration of the WIC test in terms of maximum restraint stresses and cooling rates encountered in Australian practice, it should be possible to use the test to evaluate the effect of changes in welding variables, including consumable type, and to provide guidelines on the conditions which are likely to reduce the likelihood of HACC in field welding to an acceptably low level. E9010 electrodes were used in the WIC test program, together with pre-heat in the range -10°C to 100°C and variations in restraint length from the standard 25 mm (16.4 GPa restraint stress) to 100 mm (4.1 GPa). For room temperature WIC testing all of the root welds showed cracking from the weld face under standard restraint conditions. The initiation of cracking in preheat-free test welds typically occurred 5-7 minutes after welding, indicating that, despite the development of weld metal cracking, there should be ample time under field weld conditions for clamp removal, lifting and lowering, and the deposition of the hot pass before the onset of root pass cracking. This conclusion is a conservative one since the test conditions are more severe than the field process because the simulated lifting stresses develop and are maintained during the test as the sample cools below the threshold temperature for HACC (usually considered to be <100° C), whereas the lowering process in field welding reverses the bending stress. Moreover, for typical construction conditions, the speed of manual cellulose root pass welding would be expected to ensure that lifting occurs with the root pass weld at a temperature high enough to prevent the initiation of hydrogen cracking. One of the major findings of the testing program thus far is that the cooling time from 800°C to 100°C is a very significant factor in determining susceptibility to hydrogen cracking. Cracking was not observed in WIC test samples for preheats of 40°C and higher and it is inferred that the delayed cooling time allows sufficient hydrogen to diffuse out of the weld bead to prevent a critical hydrogen level to be sustained on cooling to ambient. Increasing heat input is also expected to extend the cooling time, but variations over the range of 0.4 to 0.75 kJ/mm did not result in marked changes in cooling time. Increasing the restraint length had a similar effect to preheat with cracking being absent for all room temperature tests at 100 mm restraint length. However, pre-cooling to -10°C produced cracking under these low restraint conditions.

DEVELOPMENT AND APPLICATION OF A PORTABLE FSW MACHINE FOR WELDING OF ALUMINIUM HULL STRUCTURE

The aluminium boat- and ship-building industry in Australia and internationally has seen staggering growth in recent years, with a particular emphasis on wave-piercing catamarans for both passenger ferries and freighters. In the case of high performance yachts and luxury craft, particular attention is afforded to the "finish" of the hull and the avoidance of the "hungry-dog" appearance which is so evident on the hull and superstructure of aluminium naval vessels. A series of aluminium yacht hulls have been "moulded" to the final profile by explosively forming prefabricated aluminium panels. In the case of monohull yachts of typically 12 m length, standard panels are of sufficient length to avoid longitudinal seams. The transverse seams are subjected to plastic strains in the length of the weld, and problems relating to differential plastic flow in the heat affected zones adjacent to MIG-welded seams do not impair the appearance of the formed hull. Complete-penetration butt welds are required and the reinforcement must be removed from the welded seams prior to explosive forming. Friction stir welding has been evaluated in the construction of an innovative and patented prototype vessel [6]. The flared bow section of the aluminium planing monohull was designed to be explosively formed to the finished shape after welding of 5 mm thick panels in a vented steel mould. Sheet explosives were positioned onto the inside surface of the friction stir welded sheets, and the explosives detonated under a blanket of water. Friction stir welding was needed to produce "flush joints" with complete-penetration in a one-sided welding procedure. The welded joints were required to be virtually "invisible" in the context of the explosive-forming process.

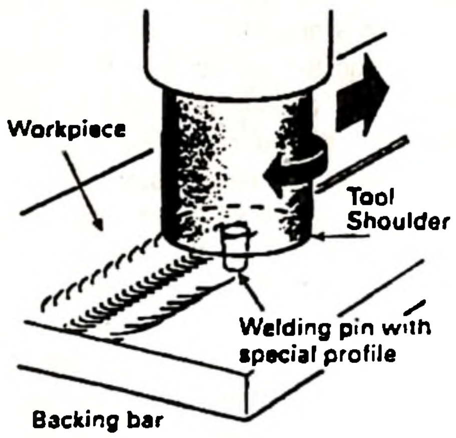

Fig. 2 : Schematic of the friction-stir welding process

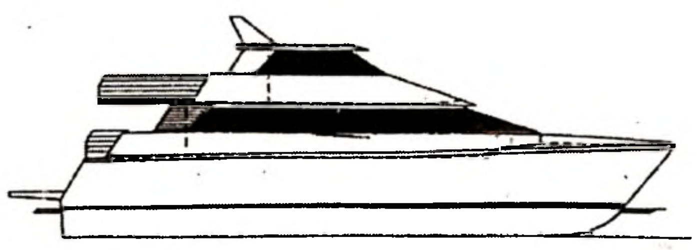

Fig 3 : Prototype 24 m ocean viewer

Friction Stir Welding process

In the friction stir welding process, a rotating non-consumable tool is introduced into the faying surface while the parts are firmly held down onto a backing plate, as shown in Fig.2. The introduction of the rotating tool heats up the metal to its plastic state.

There is only a small depression at the weld region but the transition is smooth and it does not have a deleterious effect on fatigue life. The part can be handled within minutes of welding since it is not heated to any great extent. Due to this low heat input, there is virtually no distortion. The operator skill required is not high, since it is a machine welding process. The bonding is carried out in solid state and so it is generally safe against formation of any intermetallic compounds that are normally found in fusion welds. This is an advantage in producing bonds in dissimilar joints.

Friction stir Welding of Prototype Vessel

The prototype vessel combines the attributes of a high speed luxury passenger-carrying craft with those of a semi-submersible underwater-viewing platform. The vessel is shown schematically in Fig.3, and has more than 30 knots transit speed. On reaching the underwater viewing area, a glass panelled pod (8.5 m long x 2.5 m wide x 2.5 m deep) is hydraulically lowered about 2.15 m from the belly of the vessel. In this configuration, the vessel has auxiliary drives for creeping and

maneuverability as the vessel is in close proximity to underwater features, giving excellent viewing for up to 25 passengers at a time of the total 112 passenger capacity. The principal benefit of the new concept is the low impact on environmentally sensitive marine parks such as the Great Barrier Reef off the east coast of Australia. Current practice involves permanently-moored pontoons surrounding reef atolls. High speed ferries shuttle tourists to and from the pontoons. Catering and toilets are not allowed on the pontoons, but experience has shown that this arrangement inevitably results in an unacceptable level of site contamination. In the case of the ocean viewer, the passengers are entertained on-board other than for the period that is provided for swimming or snorkeling. Another benefit is the ability to access different reefs depending on prevailing conditions and to provide tourists with a diversity of underwater viewing.

Description of the friction stir welding Machine

The development of tools and welding parameters for friction stir welding of 5 mm AA5083 marine grade aluminium plate was undertaken by TWI, whereas the design and construction of the portable FSW machine was the responsibility of the Department of Mechanical Engineering at The University of Adelaide in consultation with TWI. Modular construction was necessary to enable manual handling of individual elements and ease of assembly and set-up on joint lines. The sturdiest part of the developed machine was the beam assembly constructed from two extruded aluminium rectangular hollow sections having an overall length of 2500 mm. Beam deflection due to the substantial reaction force is unavoidable and this deflection was accommodated in a hydraulic system used to maintain a constant contact condition. A travel carriage traverses on the beam and is guided by a cluster of cam followers. The carriage is pulled up and along the beam using a winch. A lever arm on the carriage was actuated by a hydraulic cylinder to maintain the contact conditions throughout the 100 mm of lift to accommodate the curvature on the weldments. The hydraulic power pack works as a constant pressure compliant system over the stroke of the cylinder, which was necessary to friction stir weld the curved sheets underneath the straight beam. A three-roller head maintained the correct relationship between the tool and the workpieces, and also acted to press the aluminium plates against the backing jig. The shouldered tool was driven at constant rotational speed by a hydraulic motor. The entire carriage and welding head was symmetrically disposed about the axis of the beam.

Friction Stir Welding Trials

Laboratory experiments at The University of Adelaide were initiated with TWI input [7]. At an operating pressure of 14 MPa and a flow rate of 40 l/min, the high torque hydraulic motor speed was 500 rpm which resulted in a welding speed of 90 mm/min. Satisfactory welds were made using a simple jig to simulate the curvature expected in the mould at the construction site in Cairns, North Queensland. In the shipyard, further trials were conducted with marine engineers providing assistance to identify the correct orientation of the beam to ensure the axis of the shouldered tool was always normal to the weld line over the length of the joint. Sawn edges were used to achieve satisfactory fit-up, and simple dogs and wedges were used to ensure the tight fit-up of the plates during welding. Six friction stir welds were made in the bow section. Ultrasonic testing was carried out and in the case of one defective weld, the friction stir process was used to traverse the weld line to rectify the joint. In addition to these oblique welds on the curved bow plates, another 4 welds were successfully done in the downhand position to assemble the bow deck plates.

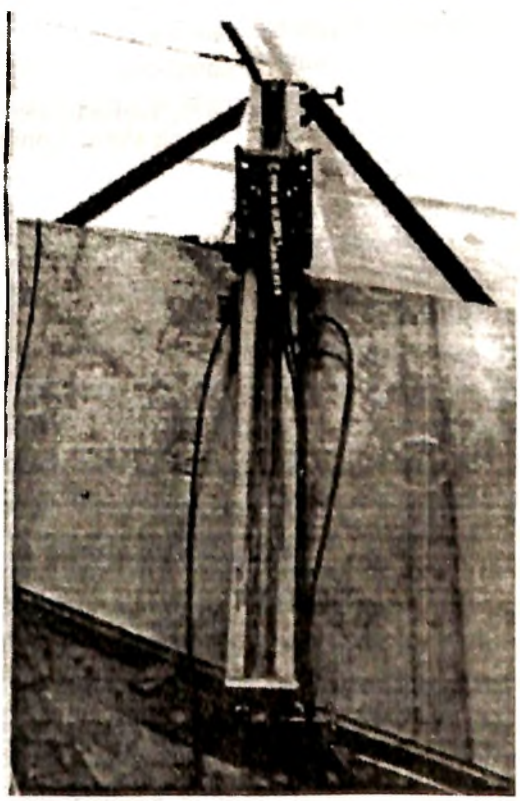

Fig. 4 : Friction stir welding of bow plates at the construction facility [7].

CONCLUSIONS

Recent developments in the Australian Pipeline Industry and the coordinated research and development program have advanced the economic use of high strength pipeline technology under Australian conditions. In the case of planar imperfections in pipe girth welds, the location and size of the flaws determine their severity in terms of the service integrity of the welded joints. Wide-plate fracture toughness testing of pipe joints containing critically-sized defects has been used to demonstrate the tolerance of weld metal to existing cracks and to crack propagation and fracture. This study has facilitated the setting of acceptable limits for defects to ensure fitness-for-purpose of pressurised pipelines. A software program, marketed commercially by WTIA as PIPESAFE, provides end users with a valuable tool for engineering critical assessment of pipeline girth welds containing defects of predetermined size. This work has also contributed to the drafting of a new Australian Pipeline Code addressing the construction of thin-walled pipelines from higher strength steels. The use of API 5L X70 and X80 steel pipe for long distance pipelines in Australia not only fosters the use of Australian made pipe, but also represents a potential saving of at least $3 M over the next 5 years resulting from lower total tonnage and reduced welding cost of thinner-walled pipe.

The timing of the release of the internal line-up clamp, which is used to position and hold the adjoining pipe lengths during field welding of the girth joints, is a key determining factor in the rate of laying of pipelines, and therefore impinges directly on the total construction cost. These aspects have been thoroughly investigated to determine the propensity for cracking in the root pass of partially-completed girth welds in relatively small diameter, thin-walled linepipe. Current practice requires that the clamp is maintained for the entire welding cycle, and that no movement of the pipe occurs until 100% of the root pass weld is completed. Under normal conditions prevailing on flat terrain, the research has shown that clamp release and movement after 50% completion of welding of the root pass is safe practice. The increase in pipeline construction rate, combined with the better utilisation of equipment and resources, is projected to save at least $100M in pipeline construction costs over the next 5 years.

The development of a marine-environment friendly, underwater-viewing vessel for operation on the Great Barrier Reef provided the opportunity to apply and evaluate the recently-invented friction stir welding process in the welding of the hull and decking of an aluminium vessel. A project involving TWI-UK and The University of Adelaide saw the design, development and application of a portable curved-plate FSW machine in the shipyard in Cairns. This project was the first industrial application of the FSW process anywhere, and has resulted in strong industrial interest from Australian and overseas companies in pursuing other applications of this technology.

FUTURE FOR COLLABORATIVE WELDING-RELATED RESEARCH IN AUSTRALIA

The success of the CRC-MWJ was an ideal platform for the launch of the new CRC for Welded Structures in July 1999, which intends to build on the established strengths and opportunities while creating new research, education and technology transfer initiatives to address the life cycle performance of welded structures. The CRC-WS which was reported on at a previous Conference [8] has the distinct advantage of 7 new core partners encompassing most of the mainland States, and the expected high levels of industrial support and involvement will ensure the collaborative research effort is directed at ensuring that the world's best-practice technology is not only available to Australian companies, but is implemented and exploited.

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