PIPELINES FOR STRANDED GAS RESERVES: CUTTING THE COST

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1. INTRODUCTION

In much of the world, natural gas competes with coal and oil as a primary energy source and when it is delivered by pipeline, can benefit from economies of scale not available to these or to LNG [1]. Being compressible without practical limit, the volume delivered by a pipeline depends upon the operating pressure at its outlet and on the pipe cross section. The amount of steel used in the pipe and many of the laying costs, however, depend on the pipe diameter and hence the square root of the cross section. The unit cost of transporting the gas can therefore be reduced by delivering more of it in larger diameter pipelines, and at higher operating pressures.

The economics of laying oil and gas pipelines differ from those of other engineering projects in that long lengths of line are laid from end to end, so that the speed with which each piece of pipe can be joined on to the line already laid determines the rate of progress of the line and how long it will take to complete it. In countries with plenty of relatively unskilled labour but no means of welding pipe at high speed, the option of breaking the line down into a large number of sections, laid in parallel and finally joined together, has sometimes been chosen. However, the difficulty of tying in such sections, misaligned and irregularly spaced as they will be, makes this an unattractive solution. Modern systems therefore rely on an ever-increasing speed of joining to hasten the day when the first fluid starts to flow through the line and generate cash to pay for it.

For most of the second half of the 20th century, the speed with which a gas pipeline could be laid was paramount but control of costs was not always so important. Prices to the consumer were high and reserves not too distant, so pipeline costs were quickly amortised, even for offshore lines. As the 21st century advances, the more accessible reserves will become exhausted and there will be a demand to bring more distant ones on stream, but these will initially have to compete with existing sources with a lower cost base. If stranded resources are to be released, and if pipelines are to remain a preferred method of gas transport, major reductions in the cost of pipelines must be achieved. This paper presents a view of some advances which will contribute to this.

2. INCREASING WELDING SPEED

The welding of mainline joints is almost always on the critical path for pipelaying, so for 70 years or more, speed of welding has been prioritised over all else. Despite the promotion over the years of many other welding processes – friction, electron beam, flash butt, magnetically impelled arc butt and laser welding to name a few – the gas-shielded metal-arc process, now mechanised and with multiple wires, has continuously expanded its capabilities to meet their challenge and remains competitive. The speed of laying ultimately depends on the effective linear speed with which the weld root can be completed, that is the actual speed multiplied by the number of welding heads. As a benchmark, cellulose electrodes can be used in the root at speeds up to about 0.75 m/min in the downward direction (stovepipe welding) [2]. Semi-automatic CO_2 welds, when they first appeared in the 1960s, were made at barely half this speed, but could compete if lowering-off did not have to await completion of the hot pass, as was required with cellulose electrodes [2]. Recent developments in control algorithms for the CO_2 process have greatly improved its usability for pipeline rooting and allowed it to be used for fully mechanised roots without backing, but procedures in the field have still only used a travel speed up to 0.3 m/min.

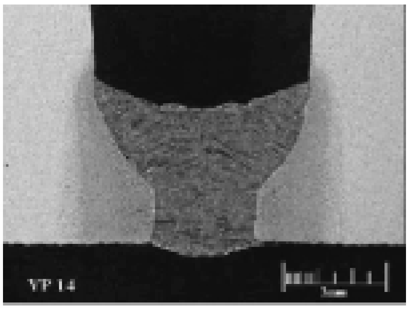


Fig 1. Root weld made using variable polarity GMAW

2.1 Root welding

New research into the control of metal transfer in CO_2 welding has allowed root welding speeds up to 1.2 m/min to be achieved in the laboratory [3]. This is one of the processes to be investigated in a new collaborative programme being undertaken by Cranfield University, The Edison Welding Institute (EWI) and the University of Wollongong. A variable polarity GMAW system developed at EWI, Fig 1, is claimed to offer similar travel speeds and will be included in the same programme.

2.2 Filling the joint

Having made the weld root at high speed, the filling and capping runs can in principle be made to keep up with the rate of progress of the pipe laying simply by increasing the number of stations on the line. In the past, when speed was more important than economy, this was a satisfactory solution, but if stranded reserves are to be commercialised, that is no longer the case. The emphasis today is on reducing the number of welding stations and the labour they employ, in order to reduce the cost of the whole operation.

Early attempts at tandem gas-shielded welding were unsuccessful because of magnetic interactions between the two arcs, but in 1975, TWI described a system they called “commutated current multiple arc welding” [3] in which pulses of current were applied alternately to two wires. At the time, the practical difficulty of producing pulsed current at continuously variable frequency restricted the application of the process, but with the development of inverter power sources for welding, the process was rediscovered. It is now used, for example, in shipyards, where it offers high deposition rates and welding speeds with low spatter and good control of the bead profile. Although multiple arc systems have not traditionally been applied in positional welding because of the difficulty of holding the molten metal in place at high deposition rates, the narrow joint preparations developed for mechanised pipe welding in the downhill direction perform this function well, extracting heat fast and providing mechanical support to the bead. Thus it has proved possible to apply multiple arc systems in pipe welding.

In shipyards, systems were developed in parallel with either a close electrode spacing, so that both wires fed into a single weld pool, or a wider spacing so that the first pool was solidifying before the second electrode passed over it. The latter technique had the metallurgical advantage that the microstructure of the first bead could be refined by the passage of the second, whereas the former risked a coarse microstructure due to the large bead size. In pipe welding, early systems used a relatively large electrode spacing, but compactness is at a premium when several bugs are to be used simultaneously on one joint, and it was soon realised that cooling rates in pipe welding would still be fast, even when two wires fed into a single pool. The key to success in this case was the development of a suitable welding torch.

The TWI commutated current system placed two electrically insulated contact tips within a single gas shroud, and Cranfield have engineered a version of this, Fig 2, which is compact and lightweight but sufficiently robust to withstand the rigours of pipe welding. It is seen from Fig 2 that long narrow contact tips are used to gain access to narrow bevel preparations in thick section materials. Several different lengths of gas nozzle are used to vary the amount of contact tip length that can extend into the bevel whilst maintaining good gas coverage. The electrodes are normally arranged one behind the other in line with the weld seam. However, they can be slightly offset or arranged transverse to the weld seam. This has been suggested for completion of wide passes in a single run.

Fig 2. Cranfield tandem GMAW torch

The principles of establishing parameters for synergic pulsed arc welding were debated in the 1970s and the simple method proposed by Cranfield [4] had a more accurate basis than some more complex methods. The pulse size and shape are established so that each pulse delivers enough energy to melt a droplet typically just smaller than the diameter of the wire. Then, by varying the pulse frequency linearly with the wire feed speed, this amount of energy will always be applied to the same length of wire and “one drop, one pulse” (ODOP) transfer will ensue over a range of mean currents. Initial pulse parameters are found by gradually decreasing the pulse time for a given peak current until droplet transfer occurs on the trailing edge of the pulse, the most stable configuration.

When one satisfactory combination of pulse height and width has been determined, others may be found using the empirical relationship $I_p^n t_p$ = constant, where I_p and t_p are the pulse current and time respectively and the exponent n approaches the value 2. In the case of commutated current welding, each pulse must occupy less than 50% of the total arc time to avoid interaction between the arcs.

2.3 Cranfield Automated Pipewelding System

Cranfield University's Welding Engineering Research Centre commenced work on tandem GMAW in 1997 with funding from TransCanada Pipelines and European Marine Contractors. This initial work involved a feasibility study investigating positional welding capability and established the productivity benefits. The welding parameters were refined in subsequent work and the design of the welding torch developed.

This work has shown that high quality welds can be made at twice the normal speed and deposition rate of conventional single wire welding in a narrow groove. Travel speeds of 1 m/min can be used for all fill passes and speeds of 1.5 m/min can be used in the 2G position.This compares with speeds of about 50 cm/min for mechanized GMAW processes currently used for pipelines. Surprisingly, it was found that the cap pass could also be welded at 1 m/min. The cap pass is normally the slowest pass with travel speeds of about 30 cm/min. Girth welds satisfying X80 mechanical test requirements were produced.

In 2001, Cranfield developed the concept of dual-tandem GMAW for pipewelding and received funding from BP Exploration Operating Company and TransCanada Pipelines to develop the Cranfield Automated Pipewelding System (CAPS). CAPS involves the use of two tandem welding torches fitted on one pipe welding bug so that four arcs operate simultaneously. The dual tandem head was fitted with a sensor based control system, removing the need for a skilled operator to continuously monitor the weld. Eventually this will be used for adaptive control of the welding process.

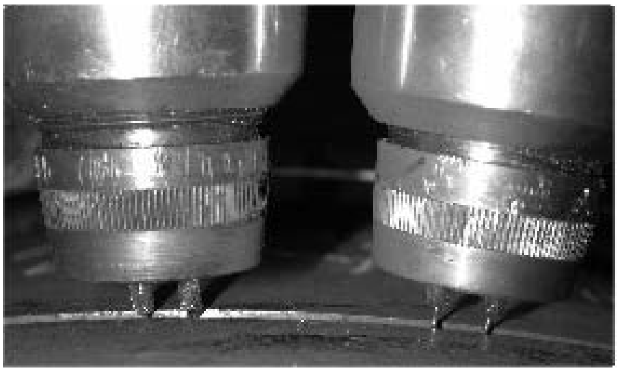


Fig 3. Spacing of CAPS dual-tandem welding torches

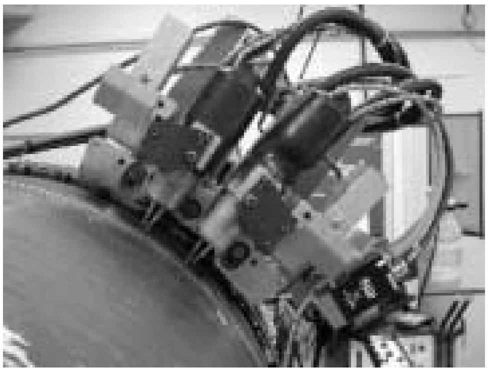


Fig 4: CAPS dual-tandem GMAW torches on RMS welding bug

CAPS involves one welding bug for each side of the pipe. Figure 3 shows the equipment setup for one welding bug. Each welding bug carries two tandem welding torches spaced 60 mm apart. This system therefore deposits two passes in each welding run. Figure 4 shows the RMS Welding Systems welding bug fitted with two water-cooled tandem torches and a laser-camera seam-tracking system. The system is currently using a welding head designed and supplied by RMS Welding Systems of Edmonton, Alberta but it can be fitted to any welding bug with dual oscillation capabilities. It is important that each torch has a separate oscillator to allow the individual layers to be deposited with the optimum oscillation width. Because of the high travel speeds, an oscillation rate of more than 400 beats per minute is required to avoid a "saw-tooth" effect with the weld bead missing sections of the sidewall.

A 48in (1020 mm) x19mm wall thickness pipe would normally require a total of 14 welding stations and would give an average productivity of 100-120 welds per 10 hour shift. The CAPS system is predicted to provide the same productivity with a total of only five welding stations.

Using an external root pass and copper internal alignment clamp, four welding stations are predicted to give an average productivity of 85-100 welds per 10 hour shift. This can be compared to a dual torch system that would give the same productivity with six or seven welding stations.

Over a long distance pipeline the saving in the number of welding stations results in a significant saving in equipment and manpower.

3. HIGH STRENGTH PIPELINES

By increasing the strength of the pipeline steel, for the same operating pressure it becomes possible to use lower wall thicknesses, resulting in lighter pipe, lower transport costs, less welding time and lower consumption of welding consumables. Alternatively, higher operating pressures can allow the use of smaller diameters for the same throughput with substantial capital savings resulting.

Until the turn of the century, the strongest pipeline material in service, X80 steel, had a proof strength of 550 MPa, and of this only some 400 km had been laid in 20 years. Since then, Transco has adopted X80 for onshore use in the UK and contractors have been able to lay it without serious problems, so this must now be regarded as the benchmark for future developments. Beyond it lie X100, with a proof strength of 690 MPa, and still higher grades with strengths of 830 MPa or more [6].

As long as 30 years ago, detailed investigation of X100 linepipe were being undertaken by Battelle [7]. The first test pipeline section of 1185 feet (361 m) of 36-inch quenched and tempered X100 pipe was installed by Atlantic Seaboard Corporation, a subsidiary of Columbia Gas System, in 1965 [8]. More recently there has been considerable activity by European and Japanese linepipe manufacturers to develop TMCP UOE X100 linepipe with a number of owner companies performing a wide range of field demonstration trials. The question of how to weld such materials in the field is now a crucial issue.

In moving to X80 pipelines from lower grades, the chief lesson that contractors had to learn was that control of all aspects of the welding process had to be more precise than for lower steel grades [9]. Weld metals have traditionally been formulated with lower hardenability than the steels they were to join, since the inherently rapid cooling of the weld pool allows them to generate relatively high strength with lean alloying. In the case of pipeline welding, this effect is enhanced when the welds are made in the downhill direction, which leads to a still faster cooling rate. As a result, even carbon-manganese consumables normally rated at 500 MPa or 70 ksi (483 MPa) minimum proof strength can produce strengths well in excess of 600 MPa in mechanised pipeline welding. When these wires are used to weld low strength pipelines, therefore, there is considerable latitude for procedural variations before there is any danger of failure to match the parent material strength.

At the X80 or 550 MPa pipe strength level, carbon-manganese weld metals can still be used but clearly the procedural tolerance is less if overmatching is to be assured. At still higher strengths, additional alloying is needed. Now there are potential penalties to be paid as alloying increases, perhaps in the form of reduced toughness or, more inescapably at normal hydrogen levels, as a reduction in resistance to weld metal hydrogen-induced cold cracking (HICC). To optimise the trade-off between strength, toughness and HICC susceptibility, the weld metal designer should be able to rely on close control of the welding parameters by the contractor. The degree to which this is possible may depend on the circumstances of welding, and it is convenient to look at three categories of weld. In mainline welding, mechanised systems will almost exclusively be used when the pipe is of high strength and large diameter, with the preferred welding direction downhill. Tie-in and repair welding may use mechanised, semi-automatic or manual metal-arc welding, most often in the uphill direction. Finally, double jointing may be carried out off line, so that the pipe can be rolled, allowing the submerged arc process to be used.

2.1 Mainline welding

For mainline welding with the mechanised gas metal-arc process, a narrow compound bevel will be used. This has a number of benefits. It reduces the joint volume, so reducing welding time and cost for a given deposition rate. It supports the weld pool as it freezes and extracts heat fast so that freezing is quick, thus allowing higher deposition rates to be used in the downhill direction without the pool over-running the arc. Moreover, the fast freezing rate increases the weld strength for a given alloy content. Figure 5 shows a comparison between the yield strengths of three types of weld metal measured in an all-weld-metal (ISO 15792-1) test at a heat input of about 1kJ/mm and in a narrow bevel joint with a closed root and an included angle of 15°, the latter welded in the downhill direction at about 0.7 kJ/mm.

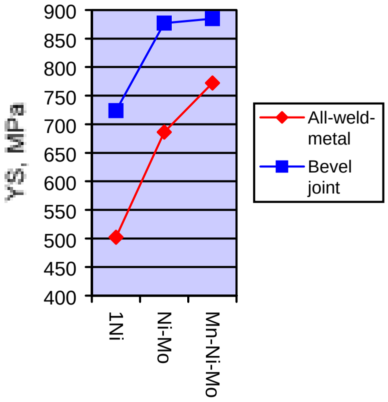


Fig 5. The effect of joint type on weld metal yield strength.

If strain-based design is employed for future pipelines, the weld metal will have to match or overmatch the real strength of the parent material, so for X100 pipe it seems that a weld metal proof strength of at least 810 MPa will be required. As the figure shows, this may be achieved with a 1.5Ni, 0.3%Mo consumable giving 690 MPa in an all-weld-metal test. As the 120 MPa of overmatching arises from the faster cooling rate of the downhill, narrow bevel joint, it is essential that this cooling rate is maintained in the field. Increasing the alloy content of the weld metal continues to increase the strength in all-weld-metal tests because the proportion of martensite in the weld microstructure increases, but in the narrow joint the structure is already highly martensitic in the low alloy material. Hence the variation in strength with joint type and welding parameters diminishes with increasing alloy content. This may not be so significant for single-wire mechanised mainline joints, which are generally closely controlled, but it is most important in tie-in welds, below. Table 1 shows an example of a relatively highly alloyed consumable, in this case a metal-cored wire, used in a compound bevel joint.

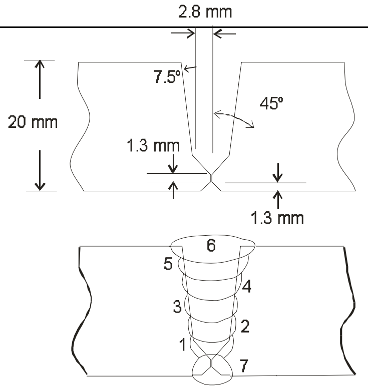
<table>
<tr><th colspan="5"><i>Welding procedure</i></th><td colspan="3" rowspan="10">
</td></tr>
<tr><td colspan="2"><i>Welding consumable</i></td><td colspan="3">EXX05, 1.2 mm</td></tr>
<tr><td colspan="2"><i>Welding process</i></td><td colspan="3">Mechanised GMAW</td></tr>
<tr><td colspan="2"><i>Preheat/interpass, °C</i></td><td colspan="3">120/200</td></tr>
<tr><td colspan="2"><i>Welding direction</i></td><td colspan="3">downwards</td></tr>
<tr><td colspan="2"><i>Shielding gas</i></td><td colspan="3">80Ar,20CO$_2$</td></tr>
<tr><td colspan="2"><i>Polarity</i></td><td colspan="3">Electrode negative</td></tr>
<tr><td><i>Run:</i></td><td><i>1-5</i></td><td colspan="3">250-280A, 26V, 0.50-0.58 m/min, 0.7-0.9 kJ/mm, no weave</td></tr>
<tr><td></td><td><i>6, cap</i></td><td colspan="3">174A, 20V, 0.25 m/min, weave 8 mm width at 0.67 Hz</td></tr>
<tr><td></td><td><i>7,sealing</i></td><td colspan="3">250A, 29V, 0.50 m/min, 0.9 kJ/mm</td></tr>
<tr><th colspan="8"><i>Mechanical properties</i></th></tr>
<tr><td colspan="2"><i>Tensile properties</i></td><td><i>PS (MPa)</i></td><td colspan="2"><i>TS (MPa)</i></td><td colspan="2"><i>El (%)</i></td><td><i>R of A(%)</i></td></tr>
<tr><td colspan="2"><i>Longitudinal</i></td><td>885</td><td colspan="2">914</td><td colspan="2">15</td><td>45</td></tr>
<tr><td colspan="2"><i>Transverse</i></td><td colspan="3">893</td><td colspan="3">Failure in w.m.</td></tr>
<tr><td colspan="2"><i>Charpy toughness</i></td><td colspan="3"><i>mid-section</i></td><td colspan="3"><i>cap</i></td></tr>
<tr><td colspan="2"><i>Cv at –40°, J</i></td><td colspan="3">69</td><td colspan="3">83</td></tr>
<tr><th colspan="8"><i>Chemical analysis</i></th></tr>
<tr><td><i>C</i></td><td><i>Si</i></td><td><i>Mn</i></td><td><i>P</i></td><td><i>S</i></td><td><i>Ni</i></td><td><i>Cr</i></td><td><i>Mo</i></td></tr>
<tr><td>0.04</td><td>0.26</td><td>2.98</td><td>0.008</td><td>0.007</td><td>1.21</td><td>0.10</td><td>0.52</td></tr>
</table>

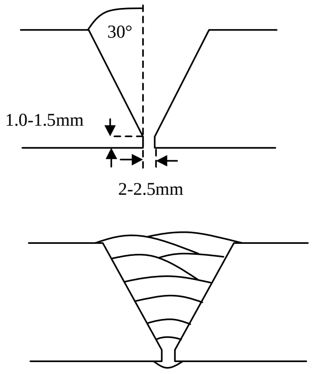
Table 1. Welding procedure for high strength pipeline using a metal-cored wire

The effect of using multiple wires in mechanised welding is clearly to reduce the weld cooling rate, so for a given strength, welding consumables must be more highly alloyed than those for single-wire welding. However, the process can be closely controlled, so it should not be necessary to provide extra alloying to allow for variability in welding parameters. The alloy system shown in Table 1, for example, is sufficiently robust to ensure the strength will overmatch that of X100 pipe in field welding with multi-wire systems. The situation for tie-in and repair welding, however, may be more challenging.

2.1 Tie-in and repair welding

Unlike mainline welds, where it is possible to rebevel the pipe ends on site and to provide internal clamps and backing systems, tie-in welds must usually be made without these aids to accurate joint fit-up. This situation leads to a preference for welding in the upward direction, which gives improved tolerance to fit-up. Wider joint preparations are used and if the weld is weaved, the heat input can increase considerably. Furthermore, if the joint width varies, as will happen under field conditions, the heat input will vary too if the joint is completed in the same number of runs. Not only will the heat input be higher and more variable than in mainline welding, but the contribution to strength from rapid extraction of heat in a narrow bevel is now absent. Nevertheless, it proved possible in the laboratory to achieve overmatching weld metal in an X100 tie-in with a shielded metal-arc root and hot pass (E11018-A1 electrodes) and a 2.7%Ni, 0.3% Mo flux-cored wire for the fill and cap passes, all in the vertical-up direction. This relied on strict control of heat input (<1.4 kJ/mm) and interpass temperature (100-120°C), Table 2.

Welding procedure

Welding consumable		Tubrod 15.09, 1.2 mm	
Welding process		Semi-Automatic GMAW	
Preheat/interpass, °C		120/200	
Welding direction		upwards	
Shielding gas		78Ar,$20CO_2$,$2O_2$	
Polarity		Electrode positive	
Run:	*Root*	SMAW, E11018-M, 76-88A, 17.7-20.0V, 65-90mm/min, 1.03-1.54kJ/mm	
	Hot pass	SMAW, E11018-M, 93-118A, 19.4-20.8V, 62-130mm/min, 1.10-1.92kJ/mm	
	3-8	FCAW, 181-209A, 26.0-26.6V, 171-333mm/min, 0.82-1.82kJ/mm	

Mechanical properties

Tensile properties	*PS (MPa)*	*TS (MPa)*	*El (%)*	*R of A(%)*
Longitudinal	746	831	16	62.5
Transverse	TS (MPa) 770, 772, 780, 772 – all failures in the parent metal			

Charpy toughness	*J at -60°C*	*J at -40°C*	*J at -20°C*
Weld root centreline	*49*	71	96

CTOD	*Weld centre*			*Fusion line*		
mm at –10°	0.14	0.11	0.12	0.26	0.18	0.16

Chemical analysis

C	*Si*	*Mn*	*P*	*S*	*Ni*	*Cr*	*Mo*
0.054	0.36	1.24	0.012	0.009	2.56	0.03	0.31

Table 2. Tie-in procedure for X100 pipeline using a rutile flux-cored wire

During the introduction of X80 pipelines in the UK, tie-in welds which met the yield strength requirement of 578 MPa could be made under controlled conditions using a wire which in a downhand all-weld-metal test produced a minimum of 620 MPa. However, under less controlled conditions typical of field welding, some contractors found they could not achieve this and opted for a wire giving a minimum of 690 MPa in the downhand position. This was more highly alloyed and formulated to produce a lower weld metal oxygen content so that toughness could be maintained. If the same philosophy of overmatching is applied to X100 tie-ins, still higher alloy contents, perhaps totalling 8-10% by weight, will be required.

2.2 New alloy development

Traditionally, welding consumables for low-alloy or microalloy steels have not been made with alloy contents greater than about 5%, so when attempting to optimise properties at richer compositions there was little past experience to rely on. Commercial electrodes with 3% nickel are widely available, and 9% nickel wrought steels combine good strength with high toughness. As a first step towards higher alloy contents, electrodes were made by adding nickel to a standard 3%Ni type, producing alloys A and B in Table 3. These turned out to have poor toughness and further development was clearly needed.

During the period in the 1960s when high strength weld metals were first being developed, statistical experimental plans such as the Box-Wilson design became popular and these have been widely used since then for the

	Weld A	Weld B	Weld C
C	0.03	0.03	0.025
Si	0.25	0.25	0.37
Mn	2	2	0.65
S	0.01	0.01	0.006
P	0.01	0.01	0.013
Ni	7.3	9.2	6.6
Cr	0.5	0.5	0.21
Mo	0.62	0.62	0.4
O	330	320	380

Table 3 Compositions of experimental SMA welds

same purpose. More recently, new techniques such as the use of artificial neural networks have become available and this was tried to see whether it had a place in welding consumable development.

Models were created from an experimental database at Cambridge University [10,11] representing 3300 ferritic welds and part of the Ni-Mn response surface is shown in Fig 6. For this compositional range, it appeared that good toughness was only to be achieved at low manganese contents. A third composition, Weld C in Table 3, was therefore made and all three are shown in Fig 6.

At this stage, the work has been regarded as a testbed for the use of neural network techniques, and much more work will be needed to demonstrate the viability of higher alloy weld metals. Enough has been done, though, to suggest that the technique can indeed offer some short cuts in development and that higher nickel contents, in particular, are an area worth exploring.

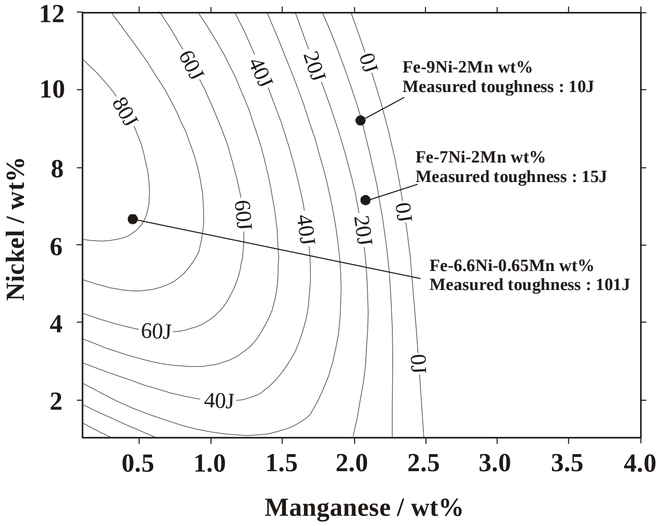


Fig 6 Neural network prediction and experimental results for the effect of manganese and nickel on toughness at –60°C

2.2 Double jointing

Double jointing – the joining of two or more pipe sections off-line, so that the line can progress two or more times as fast for a given rate of joining new sections to the line – is usually impractical in highly populated areas such as Western Europe, but pipelines designed to bring stranded resources to the market are likely to be built in areas where restrictions of space do not apply. Moreover, the economics of the procedure can make an important contribution to the viability of the project. When double jointing, the pipes being joined can be rotated so that welding is always carried out close to the horizontal position, allowing for the use of high deposition rate processes such as submerged arc welding. For offshore pipeline construction, double jointing has become very common, and it will have an important part to play where large land masses have to be crossed.

For pipe grades up to X70, double jointing presents few problems. The pipe itself is likely to have been manufactured using the submerged arc process for its seam weld, and consumables to do this are readily available. Tubular wires offer a productivity improvement of about 25% compared with solid wires, and have been used for example for on the Blue Stream project, where double jointing had to keep up with a fast-moving laybarge. To move from a longitudinal to a circumferential weld, it should at most be necessary to make a minor adjustment to the slag fluidity. For higher strengths, however, the need to ensure satisfactory mechanical properties and joint integrity outside the controlled environment of a pipe mill must be addressed. One option that has been adopted is to use mechanised gas-shielded welding, with the same narrow joint preparation that is used for fixed-position mainline welding. This allows the use of relatively low welding heat inputs. However, submerged arc welding remains the most common double-jointing method and is used in wider joint preparations and at higher heat inputs.

The previous section described alloy development aimed at increasing the tolerance of the weld metal to variations in welding parameters, and in particular to heat input variations. The situation in double jointing is not quite the same as that for tie-in welding, because welding is always mechanised and it should be possible to provide accurate and reproducible joint preparations. Thus although the heat input may be high, variation may not be the prime concern. However, another threat now appears: hydrogen cracking.

4. HYDROGEN-INDUCED COLD CRACKING

It was known 45 years ago [12], and has been forgotten and rediscovered at regular intervals since then, that the risk of weld metal HICC increases with increasing heat input. In a 1996 Cranfield programme looking at high strength weld metals, a wire/flux combination giving proof stresses above

740 MPa showed cold cracks at a heat input of 5.8 kJ/mm but none at 3.5 kJ/mm. More recently, a project coordinated in Finland [13,14] is showing submerged arc welds to be more susceptible than manual metal-arc welds. Initially, it was thought that this was due to comparisons being made at different strength levels, but further tests at ESAB now suggest that this may not be the case.

Tests are carried out using a heavily restrained U-groove specimen designed by VTT. In order to enable the effects of interpass time and temperature to be separately evaluated, provision is made for the welds to be cooled with dry ice where necessary, Fig 7.

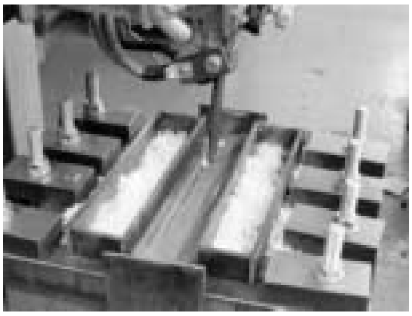


Fig 7 Assembly for testing welds for HICC, with removable clamping and dry ice cooling

Using this test, it proved possible to generate transverse cracks in weld metal of 760 MPa proof stress and less than 5 ml/100g diffusible hydrogen at interpass temperatures up to 200°C and an interpass time of 5 min. The cracks were surface-breaking or immediately below the surface and typically appeared up to 24 h after the end of welding. The conditions, using highly restrained 70 mm thick plate, were severe and similar consumables have been used in less rigorous circumstances without cracking, but this is an indication that a new approach to the control of weld metal HICC is needed.

It has been known for some time that at moderate to high hydrogen levels, the susceptibility to embrittlement of the weld metal is largely a function of strength [15]. As the strength increases, changes in the microstructure can do little to alleviate the increasing tendency to cracking. However, it has also been found that at very low hydrogen levels, a change in behaviour occurs so that the influence of microstructure now predominates over that of strength. More work will be needed to define the precise hydrogen level at which this transition occurs, but it appears to be below 5 ml/100g.

In work at Leeds University [16,17], cylindrical specimens were machined from a range of weld metals and degassed for 20 h at 150°C to remove hydrogen. Some were then electrolytically recharged with hydrogen to nominal levels of 1.5, 3 and 4.5 ml/100g. Tensile tests were then carried out to compare the strength and ductility of charged and hydrogen-free specimens.

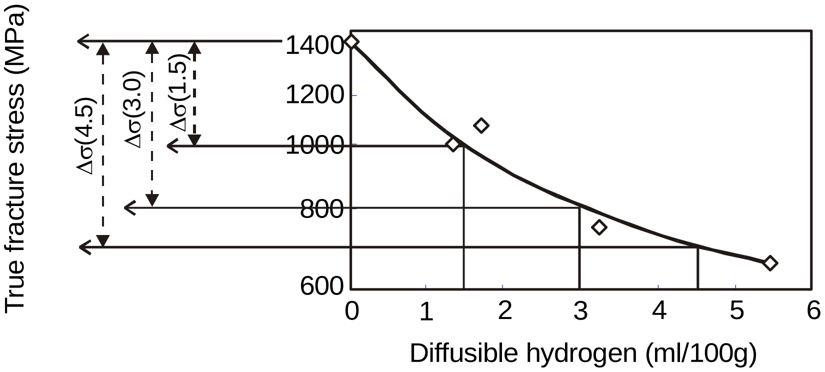


Fig 8 Measures of reduction in true fracture stress as a result of hydrogen charging

Weld metals were characterised by the ratio of true fracture stress after hydrogen charging to that in the uncharged state, Fig 8. At the 4.5 ml/100g hydrogen level, the ratio of charged to uncharged true fracture stress was not statistically correlated with composition, but when plotted against the Ito and Bessyo pcm factor [18], a possible trend to lower ratios with higher pcm could be discerned, Fig 9. Two of the welds did lie below the trend line, one of these being characterised by a high level of grain boundary ferrite, in which hydrogen cracks have often been observed to form. It seems likely that the 4.5 ml/100g hydrogen level is at the transition point between hardness- controlled hydrogen embrittlement, demonstrated by Hart [15] at the 10 ml/100g level, and microstructure-controlled embrittlement, found at lower levels by Hart and in Wildash's work described here.

If the results for a hydrogen level of 1.5 ml/100g are plotted in the same way, the trend appears to be reversed, Fig 9, indicating that a microstructure-controlled regime is now operating. Quantitative metallography was used to look at all the welds and some results are shown in Fig 10.

The test results are here presented in order of increasing yield strength from 400 to 988 MPa. It is immediately clear that there is no trend in fractional loss of fracture stress with strength. The softest weld shows the most embrittlement, and coincidentally the highest amount of grain boundary ferrite. As the strength increases, no trend in loss of fracture stress is seen until the yield strength

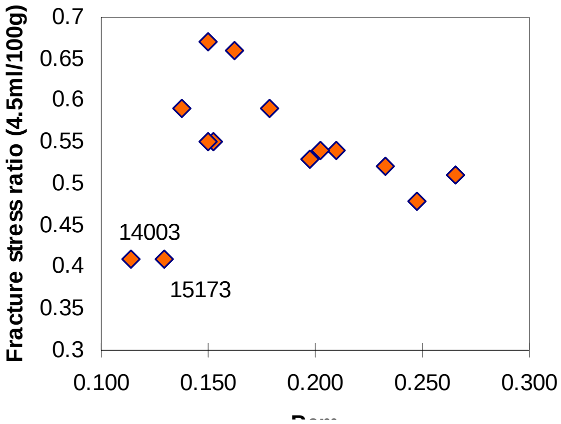


Fig 8. Reduction in fracture stress as a result of hydrogen charging at 4.5 ml/100g

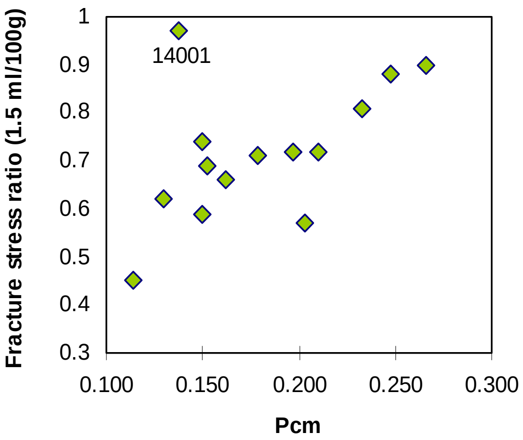


Fig 9. Reduction in fracture stress as a result of hydrogen charging at 1.5 ml/100g

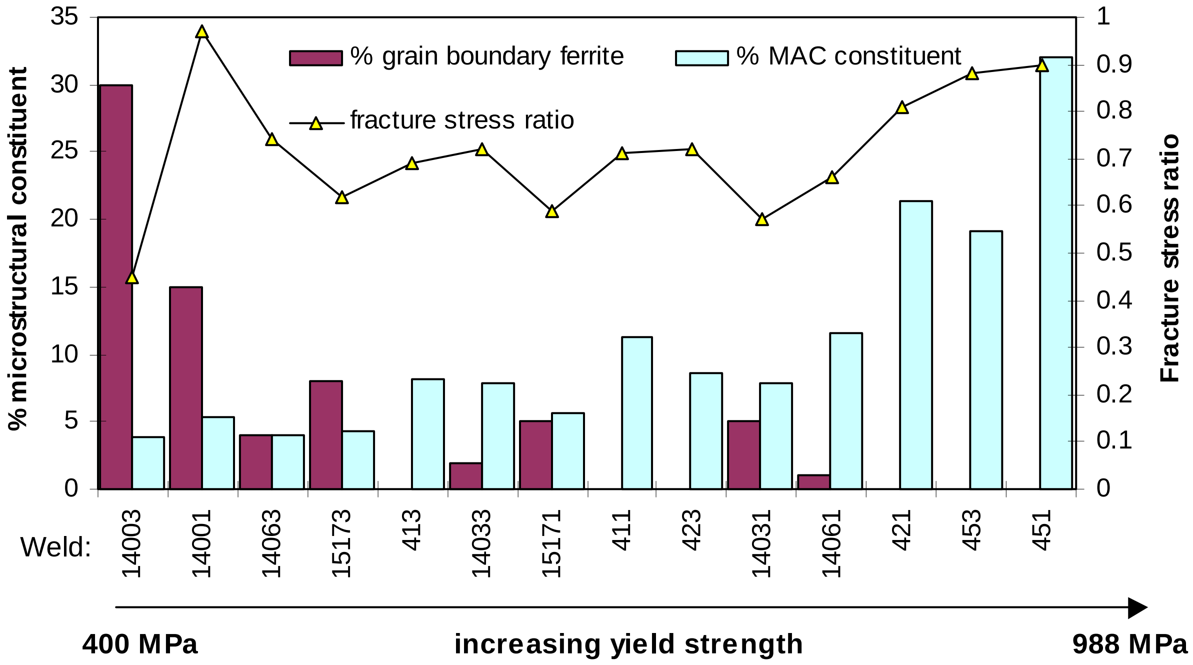


Fig 10 Reduction in fracture stress of hydrogen-charged specimens, after Wildash [16]

reaches 675 MPa (Weld 14031), after which the embrittlement decreases as the strength increases. At the same time the proportion of the so-called “MAC” (Martensite-Austenite-Carbide) constituent in the microstructure is increasing. This by itself is not conclusive evidence of the benefits of MAC constituent, but experimental consumables subsequently formulated to give enhanced MAC levels also showed improved resistance to hydrogen embrittlement. This may be due to the ability of MAC constituent to act as sinks for hydrogen, removing it from more susceptible sites in the microstructure. The work on 7% Ni consumables described in the previous section was partly inspired by this possibility, as these weld metals can also contain significant amounts of retained austenite.

It is of course possible to weld X100 and stronger pipelines with existing welding consumables provided sufficient preheat is applied, and with plans for “onshore laybarges” to provide still more control and automation of the process, this should be feasible. The latest work, however, indicates to a great incentive to reduce hydrogen levels still further, leading to a regime where large strength increases will not incur any penalties in terms of hydrogen embrittlement.

5. DISCUSSION

One of the keys to meeting global targets for CO_2 emissions in the coming years will be the substitution of natural gas for more carbon-rich fuels, and this must involve significant unlocking of resources that are at present stranded. Not all of these will be suitable for transport by pipeline, and the LNG and GTL technologies will certainly play their part. Pipelines will only come into their own when the volumes to be transported are large, and that means aggregation not only of resources but also, at the other end of the pipe, of markets. However, there are many areas where this requirement is or will soon be fulfilled, perhaps most imminently for the Alaskan North Slope reserves. Pipelines then offer not only the technical advantage of economy of scale, but also the reassurance that pipelining is a mature technology which has produced remarkable advances in speed and economy of laying by incremental improvements to well-tried methods.

Over the last few years, a revolution in pipeline construction has seen increased mechanisation and process control, already commonplace offshore, introduced into onshore construction. This has happened even in the USA, which has previously avoided mechanised welding for traditional and social reasons, and in the UK, where the smaller scale of operations and limitations on rights-of-way had hitherto been thought to rule out mechanised welding. One result of this has been to facilitate the introduction of X80 pipe steel with a minimum proof strength of 550 MPa. The use offshore of tandem arc welding systems is the next technology to be replicated in onshore operations and this will produce further improvements in pipeline economics with a minimum of risk.

Beyond this, significant cost reductions are expected from developments that are only now moving to the stage of field trials. The speed of laying pipe depends on the rate at which the first weld pass can be made, and this has hardly changed in 40 years. Several new techniques, of which two are being actively investigated in a current programme at Cranfield University, offer the promise of doubling the rooting speed.

The next logical step after tandem arc welding for the filling and capping weld runs is to mount two tandem torches on a single carriage to produce a “dual tandem” system. Early trials suggest that this can indeed reduce the number of welding stations by 50% or more. Full-scale testing and parameter development are now proceeding.

Pipeline owners have taken a conservative view of steel developments in the past, as the 20 year history of the introduction of X80 demonstrates. It seems that X100 steel is now at the end of a similar, or perhaps even longer gestation period and that we shall shortly see the first commercial X100 lines. This will require a significant metallurgical input to ensure that the welding process is robust both in terms of achieving the specified properties and in avoiding cracks and other defects. Much of the groundwork has already been done and if contractors are prepared to work closely with research laboratories and welding manufacturers, success should be within our grasp.

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