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CONSUMABLES FOR WELDING HIGH STRENGTH PIPELINE STEEL

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Abstract

Some problems in applying traditional welding methods to modern high strength steels are described. Because of its potential for good penetration, submerged arc welding can allow relatively heavy sections to be welded with low consumable consumption. However, the high dilution that this implies means that when welding lean parent materials, ever higher wire alloy contents must be used to generate the high strength sought in the weld metal, and an investigation into new, high-alloy compositions is described. Consumable development must also go hand in hand with process development, in pipe mills and in the field, and some tests with synergic cold wire welding are reported.

Mainline girth welding with mechanised gas metal-arc systems can make use of downhill welding in very narrow compound bevel joint preparations, which extract heat from the weld so fast that lean weld metals can be produced for very high strength steels. Tie-ins are another matter. In this case, beveling and fit-up are less precise and uphill welding must often be used. Combining good weldability with strength, toughness and resistance to hydrogen cracking is not easy but great progress has been made over the last few years.

New developments such as laser and hybrid laser welding for pipes may be closer to commercialisation than we think, and consumable manufacturers have been busy for some years working on consumables for these.

Introduction

Microalloying of steels has brought many benefits to their users. By allowing steelmakers to achieve higher strengths with leaner compositions, it has resulted in a generation of strong, tough and relatively economical steels which, moreover, appear to have excellent weldability. For welding consumable manufacturers, however, this good news comes at a price. They do not have the luxury of being able to use thermomechanical processing (TMCP) to enhance the properties of weld metal, so they still have to rely on “old fashioned” alloying. Furthermore, some modern design codes for pipelines are strain-based, which means that the weld metal must always be stronger than the steel being welded. The result is that today’s weld metals are often more highly alloyed than parent materials, with greater susceptibility to hydrogen-induced cracking, and manufacturers face a real challenge in achieving the required combination of strength and toughness. This paper describes how the challenges are being met in seam welding and girth welding of high strength pipe steels.

Forty years ago, penstocks for the Snowy Mountains hydro-electric scheme in Australia were made using steel with 690 MPa minimum yield strength and, while there were a few welding problems, there was a general view that many more projects using this and similar high strength steels would quickly follow. An experimental 360 m length of X100 (690 MPa yield strength) pipeline was installed in West Virginia by Atlantic Seaboard Corporation in 1965 and forms part of a pipeline which is still in service. These steels were quenched and tempered, and it was not difficult to find manual metal-arc electrodes with similar total alloy contents that could be used to weld them. There was no insistence on overmatching strength for the girth welds, and indeed in the case of penstocks it was discouraged.

Another short length of X100 pipeline was laid in Canada in 2003, followed in 2004 by a 2 km section. This time, although the mainline joints caused no difficulty, potential problems have arisen during further procedure tests for tie-ins, where no in-situ beveling is possible, and double jointing, where two pipe lengths are joined off-line by submerged arc welding. These problems are of a different nature from those overcome forty years ago. Ironically, they arise partly from the introduction of improved, "more weldable" steels, which make it hard to develop sufficient strength when the weld dilution is high. In Alaska, Canada and Siberia, the decision to lay buried pipelines in ground subject to seasonal freezing leads to consideration of longitudinal stretching of the pipe due to "frost heave", so strain-based design is applied. The weld metal must then overmatch not only the nominal minimum yield strength of the parent material but its actual maximum strength, currently estimated as 700 MPa for X80 pipes.

At the opposite end of the scale from submerged arc welding, beam processes such as laser welding can achieve high travel speeds with very low heat inputs. Here, the problem is how to limit the weld metal strength and develop satisfactory ductility and toughness.

Pipeline girth welding

The economic need to lay pipelines faster and the introduction of higher strength steels which are no longer suited to stovepipe welding have resulted in the widespread adoption of mechanized gas metal-arc welding (GMAW) for pipeline construction. So successful has this proved that none of the alternative methods proposed over the last forty years – friction, electron beam, magnetically-impelled arc, laser, flash and explosive welding to name only the most widely canvassed – has succeeded in supplanting it on any significant scale.

One advantage of mechanised GMAW welding arises from the use of downhill welding at low heat input in conjunction with a narrow joint preparation. This results in very fast weld cooling rates, with $\Delta T_{8\text{-}5} \sim$ 3-4s. As a result, it is possible to achieve a weld metal yield strength in excess of 700 MPa using no more alloying than 1.6%Mn, 0.65% Si in the wire. In practice, users generally opt for a wire containing 1%Ni, 0.4% Mo when welding X100 and, when strain-based design applies, X80 pipes, but mainline welding is rarely a source of concern.

Pipeline tie-ins, on the other hand, are traditionally made using uphill welding because, with no opportunity to use internal clamps or rebeveling, this gives greater tolerance to fit-up variations. In this case, the heat input may be high and the weld metal strength may be lower than would be reported in a consumable manufacture's batch test according to ISO 15792-1.

The use of rutile flux-cored wires for tie-ins was pioneered in offshore pipe laying and was soon adopted for onshore lines. Onshore pipe strengths can be higher, with X80 in regular use in the UK. Some contractors, used to dealing with lower strength steels, did not establish at the outset the culture of control which is essential at higher strengths. Initially, a 2%Ni, 1.4%Mn wire was tested, and with good control of heat input and interpass temperature, this proved satisfactory for X80 tie-ins. However, some contractors failed to achieve the required yield strength of 578 MPa because their heat input was too high, so a wire with 1.2%Mn, 2.6%Ni, 0.25Mo was introduced[1]. This was found to be more tolerant to welding parameter variations and was subsequently adopted by all contractors.

Twenty years ago, it was believed that a yield strength of 550 - 600 MPa represented a practical upper limit for rutile flux-cored wires, because the oxygen content needed to reduce the droplet surface tension and so allow spray transfer was too high for acceptable toughness above this. Today, fine tuning of deoxidation systems allows the production of wires giving a yield strength above 700 MPa, one of which has been approved for X100 tie-ins.

For still higher strength steels, and where a high degree of overmatching is needed on X100, a satisfactory strength/toughness compromise can at present only be reached by reducing the weld oxygen content to a point where a rutile wire develops the globular metal transfer normally characteristic of a basic wire. Welding manufacturers are working on a solution to this problem, and at present it seems that the use of intelligent power sources, probably using a pulsed arc, will make a contribution.

Submerged Arc Welding

Table I shows a series of high strength steels.

Table I. Composition of high strength steels.

YS	Steel type	Chemical composition									CE (IIW)	Pcm
		C	Si	Mn	Cr	Mo	Ni	Nb	Ti	B		
550 MPa	Q1N 1968	0.15	0.23	0.27	1.35	0.31	2.46				0.69	0.28
	Europipe 1992	0.09	0.40	1.94	0.05	0.01	0.03	0.043	0.017		0.43	0.21
	Campipe 2003	0.045	0.26	1.6		0.26	0.27	0.054			0.40	0.16
690 MPa	NA-XTRA 70	0.16	0.24	0.9	0.31	0.4		0.027		0.0017	0.45	0.26
	Europipe X100	0.06	0.35	1.9		0.28	0.25	0.05	0.018		0.45	0.19

The first is a quenched and tempered steel used by British naval shipyards in the 1960s for submarine construction. The second, giving the same strength, was used for the first X80 pipeline for Ruhrgas in 1992-3[2]. The third is a modern X80 steel recently tested in ESAB's laboratories.

At the higher strength level, the first steel is a quenched and tempered type, popular for 40 years and still performing well in a recent joint industry project, while the second is a published composition for thermomechanically processed (TMCP) X100 pipeline steel[3]. At both strength levels, the reduction in carbon level over time leads to a significant reduction in Pcm factor[4], which is generally thought to confer benefits in weldability for high strength, low alloy steels. The reduction in carbon equivalent is less marked.

When laying pipelines, the rate of advance across the terrain depends on the number of joints that can be welded in a given time and the length of the pipe sections. If longer sections can be used, for example by joining pairs of 12 m lengths from the mill off line to produce 24 m lengths, the speed of laying can be increased. Traditionally, for steels of low to medium strength, this has been done using the submerged arc process at a heat input of 2.5 kJ/mm or more, using a root face of 8 mm. This leads to high dilution in the root area of the weld. The technique was tested on the low carbon X80 steel in Table I using a range of submerged arc wires with total alloy contents ranging from 4.2 to 6.7%, Table II. The pipe was 15 mm thick and the preparation was a symmetrical double vee of 90° included angle. The welding procedures are given in Table III.

Table II. Wires used in double jointing tests on X80 steel

Wire	C	Mn	Si	P	S	Cr	Ni	Mo	Total alloy
SpoolArc 95	0.04	1.64	0.34	0.005	0.004	0.095	1.71	0.35	4.2
SpoolArc 100	0.14	1.96	0.08	0.008	0.004	0.36	2.50	0.49	5.5
SpoolArc 120	0.08	1.63	0.32	0.010	0.005	0.34	2.33	0.48	5.2
SpoolArc 140	0.10	1.57	0.39	0.005	0.007	0.87	2.90	0.88	6.7

Table III. Welding parameters for circumferential submerged arc welds on X80 pipe

	Inner weld					Outer weld				
Weld	Wire	Amps	Volts	Travel speed (m/min)	Heat input (kJ/mm)	Wire	Amps	Volts	Travel speed (m/min)	Heat input (kJ/mm)
18923	SA95	650	32	0.51	2.5	SA95	780	32	0.43	3.5
18924	SA100	650	32	0.51	2.5	SA100	650	32	0.51	2.5
18925	SA100	650	32	0.51	2.5	SA100	650	32	0.43	2.9
18922	SA120	650	32	0.51	2.5	SA120	780	32	0.43	3.5
18938	SA140	550	35	0.41	2.8	SA140	550	35	0.41	2.8

In undiluted welds, these wires should have produced yield strength levels ranging from 640 to 930 MPa, but as a result of the high dilution and heat inputs, the actual range was only from 573 to 586 MPa, Table IV. The tensile strength shows a greater variation but this does not help where design is strain-based.

Table IV. Test results from circumferential submerged arc welds on X80 pipe

Weld	Inner wire	Outer wire	YS MPa	TS MPa	Elong %	Cv, J at -29°C	Weld metal analysis					
							C	Mn	Si	Cr	Ni	Mo
18923	SA 95	SA 95	573	672	24	89	0.05	1.64	0.34	0.04	0.79	0.29
18924	SA 100	SA 100	584	719	26	152	0.06	1.66	0.27	0.11	1.00	0.34
18925	SA 100	SA 100	573	714	25	156	0.06	1.66	0.28	0.12	1.06	0.35
18922	SA 120	SA 120	585	705	24	132	0.06	1.64	0.37	0.13	1.09	0.35
18938	SA 140	SA 140	586	754	23	101	0.06	1.59	0.36	0.30	1.20	0.47

Knowing the wire and parent material compositions, it is easy to calculate the weld metal dilution, which is found to be about 65%.

To put these figures in perspective, they are superimposed in Fig 1(a) on the results of a 1994 test programme at ESAB aimed at developing high strength submerged arc weld metals. This produced a regression equation for yield strength in terms of composition, which has been used elsewhere for predictive purposes. As can be seen, the welds in Table IV are not out of line with previous experience, given their composition. However, using the regression equation and knowing the weld dilution, it is a simple matter to calculate what the strength of the welds would have been if they had been made on the earlier X80 pipe material or on the quenched and tempered steel, Fig 1(b).

This shows that modern steels with very low carbon contents make it difficult to achieve the overmatching weld metal yield strengths which are increasingly demanded in pipeline welding. In normalised steels, the carbon content has very little effect on yield strength, but in these weld metals it has a powerful strengthening effect which is not compensated for by the extra manganese diluted from the TMCP steels. Consumable manufacturers have patented ultra-low carbon bainite filler materials[5] which may help, but these still need rather high levels of nickel and molybdenum to achieve high strengths.

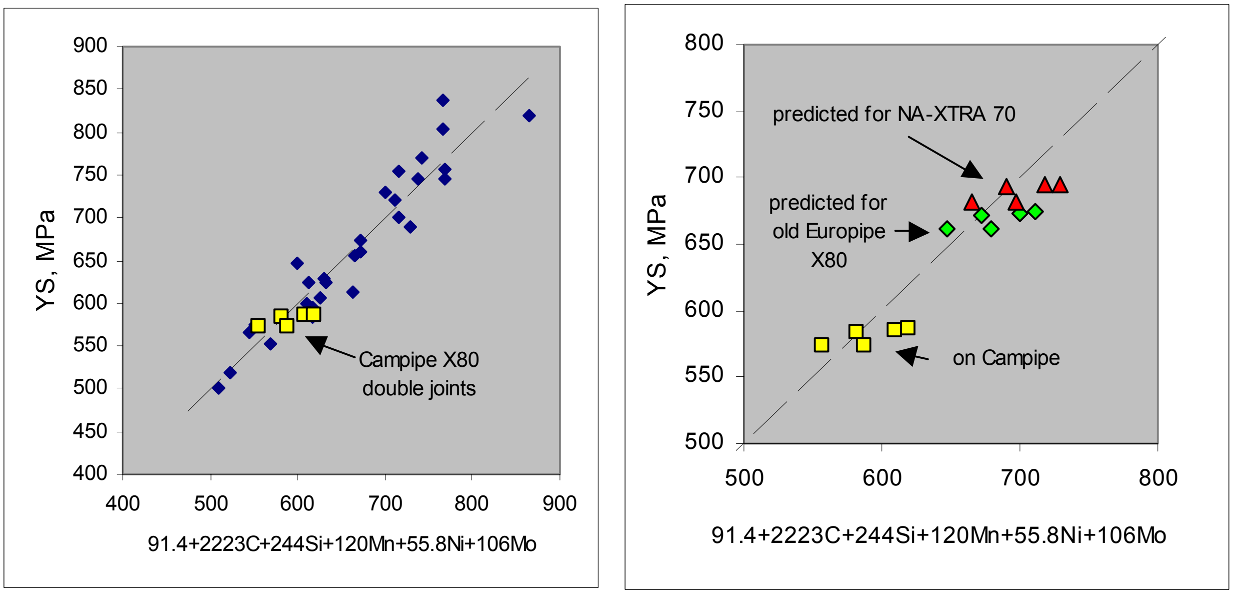


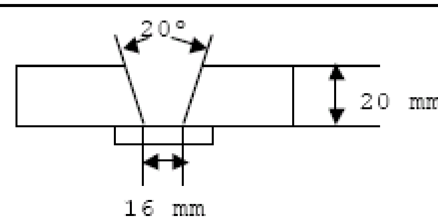
Figure1(a) Strength of double joint shown on a regression plot of submerged arc weld metal strength against composition.

(b) Showing predicted effect of dilution if the same wires are used with other base material compositions

Synergic Cold Wire Welding

There are ways to increase the productivity of submerged arc welding while minimising these deleterious effects. One of these is the use of a cold wire addition in submerged arc welding.

Table V Welding details and productivity comparison between conventional SAW and SCW for an ISO joint in 20 mm plate.

Parent material	Mild steel			
Joint configuration				
Consumables	OK Autrod 12.22/OK Flux 10.71			
Process	SAW	SCW	SAW	SCW
Polarity	DC+	DC+	AC	AC
Electrode *F* (mm)	3.0	3.0	3.0	3.0
Cold wire* *F* (mm)	-	2.0	-	2.0
Current	500 A			
Voltage	32 V			
Travel speed	55 cm/min			
Heat input	1.75 kJ/mm			
Effective heat input	1.75 kJ/mm	1.21 kJ/mm	1.75 kJ/mm	1.21 kJ/mm
Weld passes	20	13	18	12
Relative deposition rate	100%	154%	100%	150%

* leading cold wire

First described in 1975[6], the process was recently refined[7] to become synergic cold wire (SCW™) welding. In this system, a cold wire is fed into the weld pool either ahead of or behind the wire carrying the arc current. The feeding rate of the cold wire is fixed in relation to that of the current-carrying wire, thus making setting up easier for the operator.

In tests using ISO joints in 20 mm plate, SCW welds were compared with conventional single wire welds. A single 3.0 mm wire filled the joint in 20 passes using a heat input of 1.75 kJ/mm, while with the addition of a cold 2.0 mm wire, the joint was filled in only 13 passes at a heat input of 1.21 kJ/mm, Table V.

Thermal measurements were carried out in Type 316 stainless steel, where cooling rates are about 58% slower than in low alloy steel because of the lower thermal conductivity of the austenitic material. The results, Fig 2, showed that for any given set of arc parameters and travel speed, the addition of a cold wire increased the weld cross section, hence the deposition rate, without affecting the cooling rate[8]. The corollary of that is that the heat input can be lowered to increase the cooling rate while maintaining the same productivity. Synergic cold wire welding is still in the early stages of its application to high strength steels and double jointing may be a promising area for the technique.

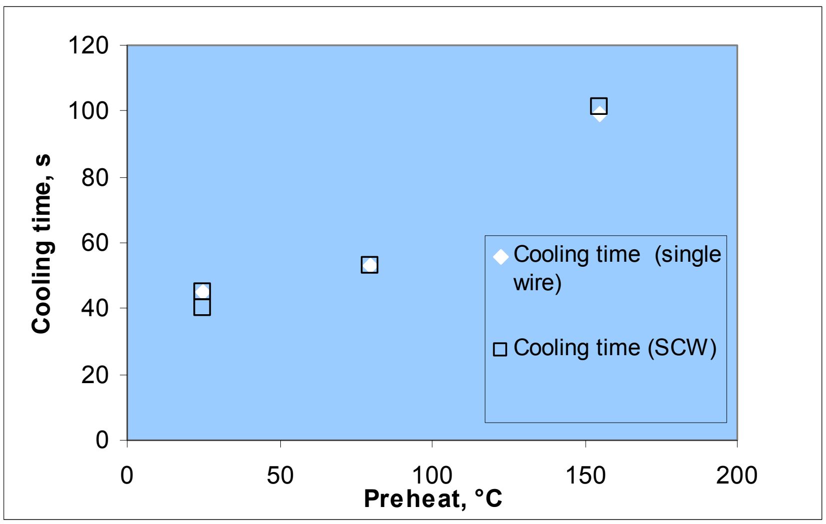


Figure 2. Showing that the addition of a synergic cold wire does not change the weld cooling rate.

Pipeline seam welding

Like girth welding, submerged arc pipeline seam welding is a high dilution process where a similar potential exists for loss of weld metal strength and toughness. In this case, the problem is alleviated by the fact that the seam weld is normally treated using stress-based design. Whereas longitudinal stretching of the pipe, for example due to frost heave or spooling, can impose severe strains on undermatching weld metal in girth welds, circumferential stresses should never exceed the nominal yield stress of the pipe, which consequently should be all that the weld metal needs to match. This should not present major difficulties. However, the weld heat affected zone (HAZ) is another matter. With modern TMCP steels, which develop their strength through a carefully applied sequence of rolling and controlled cooling, the HAZ of high heat input welds can soften to well below the strength of unaffected pipe material. This phenomenon may then become critical in determining the seam welding procedure.

Synergic cold wire welding has been proposed for pipe seam welds, but it is too early to say whether it will deliver the anticipated improvements. There is, however, another way of increasing deposition rates without increasing heat input: the substitution of tubular wire for solid wire in submerged arc welding. This has been successfully employed in pipe mills and offers some interesting metallurgical benefits.

For weld metals up to around 600 MPa yield strength, which includes most seam welds in X80 pipe steels, the preferred microstructure to optimize strength and toughness is acicular ferrite. As was pointed out in the 1970s, that is especially true when niobium is picked up by dilution from microalloyed parent materials[9].

A problem arises when high dilution welds are made with basic fluxes. As is now well known, acicular ferrite needs to nucleate on non-metallic inclusions in the weld metal. Although the mechanism is not now believed to be as simple as was once thought, the observation that the presence of sub-oxides of titanium is particularly beneficial remains. However, dilution with a very clean parent steel can reduce the total number of weld metal inclusions to a level at which ferrite nucleation becomes difficult. Using a tubular wire under submerged arc flux, it becomes possible to add oxides to the weld pool. Moreover, by using a combination of titanium oxides and strong deoxidants, the quantity of weld metal inclusions can be buffered against variations in the parent steel by a process analogous to acid-base buffering in aqueous solutions[10]. In a wire with 1.5%Mn, 2%Ni, 0.3%Mo and a boron addition, the alloying would produce high hardenability in a wrought steel and is sufficient to prevent pro-eutectoid ferrite formation even at high heat inputs. However, the large number of nuclei available in a buffered system ensures that acicular ferrite is produced in the weld metal before any lower temperature transformation products have a chance to form. This makes weld metals of this type very tolerant to dilution and extremes of heat input.

In a pipe mill making X-65 pipe, using a 3-wire welding system at a combined current of 3450A and a heat input of 7.0 kJ/mm, difficulty had been experienced in achieving the required charpy value of 47 J at –30°C with solid wires. When Tubrod 14.53, a buffered tubular wire, was substituted, using a semi-basic alumina flux, the average charpy value rose to 150J at –30°C and 47 J at –80°C.

An alternative way of achieving the best toughness in pipe mills is to match flux basicity to particular batches of steel so that optimum inclusion contents can always be achieved with solid wires. This can prove more economic than the use of tubular wires, so sales of tubular wires to pipe mills must still be counted in hundreds, rather than thousands of tonnes. However, the technology is now proven and available for use if HAZ softening requires an increase in the thermal efficiency of the welding process.

Higher alloy systems

If no means are available to restrict the thermal cycle of the weld so as to guarantee the weld metal properties, in the last resort it may be necessary to increase the total alloy content of the weld metal. Investigations at ESAB have been attempting to gain an understanding of a wider range of alloying than has been traditional for ferritic steels, and the use of artificial neural networks has helped to progress this work[11].

Nickel has long been known to be useful for increasing the tolerance of weld metals to high heat inputs because it increases the hardenability without giving rise to secondary hardening. A series of electrodes containing 6.8% Ni was tested at varying levels of heat input and interpass temperature and did indeed allow the strength to be more successfully maintained, Fig 3. However, optimizing the toughness of the weld metals required more work.

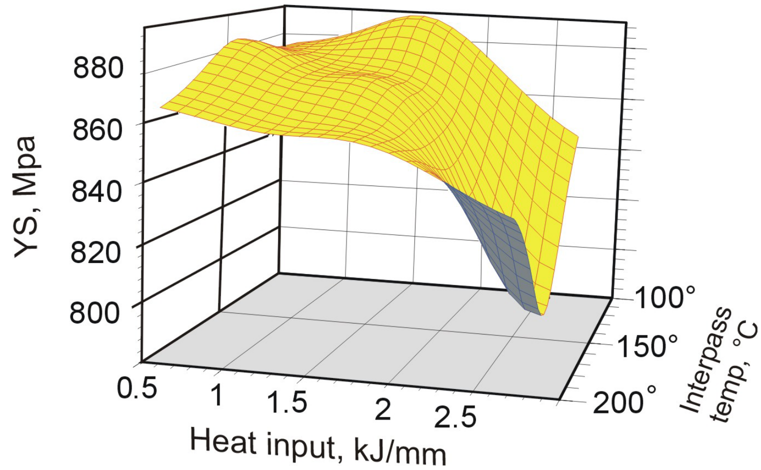


Figure 3. Heat input and interpass temperature versus yield strength of for 6.8% Ni weld metals.

As a starting point, nickel was added to A standard 3% Ni electrode to raise its nickel content to 7 and 9%, welds A and B in Table VI.

Table VI. Composition of high nickel weld metals.

	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 (ppm)	330	320	380

The toughness of welds A and B was poor, 15 J and 10 J respectively at –60°C. To investigate these results, use was made of a database of 3300 ferritic welds at Cambridge University[11] and a section of the Ni-Mn neural network response surface is shown in Figure 4.

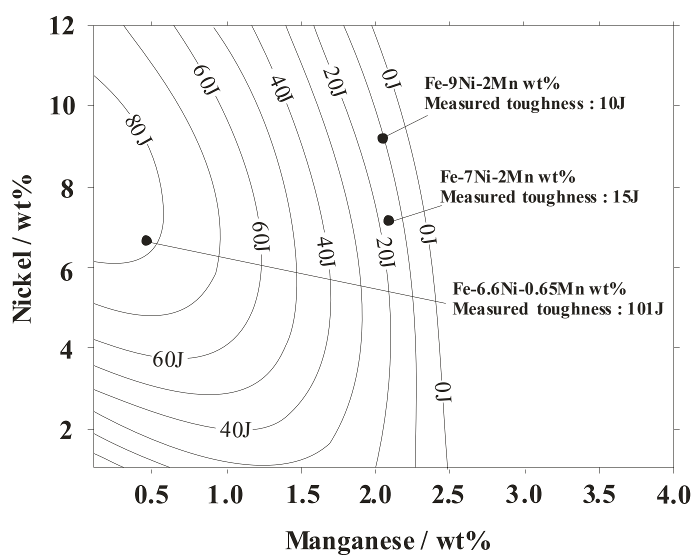


Figure 4. Neural network prediction and experimental results for the effect of manganese and nickel on toughness at –60°C

Noting that the neural network prediction was that the toughness could be greatly improved by reducing the manganese level, this was done and the average charpy value increased to 101 J. However, although neural networks can sometimes offer a short cut to improved properties, they do not necessarily throw light on the mechanisms involved. For that, traditional metallography is needed.

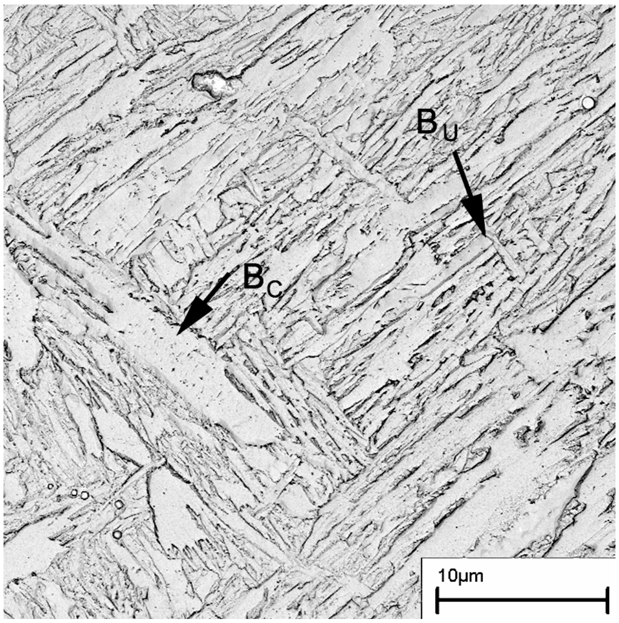


Fig 5(a) 7%Ni, 2% Mn weld metal showing coalesced bainite, B_C, after Keehan[12].

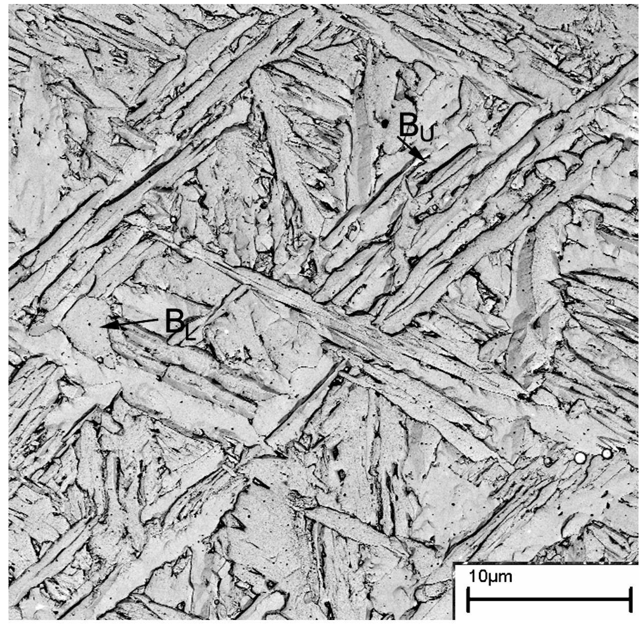


Fig 5(b) 7%Ni, 0.6% Mn weld metal consisting mainly of acicular ferrite, upper and lower bainite.

The samples shown in Table VI were examined[12] using field emission gun scanning electron microscopy (FEGSEM) and some results for specimens A and C are shown in Figure 5.

It now emerges that at the higher manganese level, where the B_S and M_S temperatures are close and there is a high degree of undercooling below Ac_3, a previously unreported constituent designated "coalesced bainite" is formed. Bainite platelets coalesce behind a rapidly moving transformation front to give larger grains, which seem to have an adverse effect on toughness.

More work will be needed to understand fully the metallurgy of weld metals at this intermediate level of alloying. They will certainly be more expensive than conventional low alloy materials, and although they can be made robust in terms of strength and toughness, their resistance to both hot cracking and hydrogen-induced cold cracking will need to be verified. Nevertheless, the market's move towards leaner steels and higher productivity may make such consumables a useful weapon in the fabricator's armory.

Hydrogen-induced cold cracking (HICC)

A by-product of the trend towards leaner parent materials, which are becoming more resistant to hydrogen embrittlement, is that the weld metals, for which no thermo-mechanical processing is possible, remain more highly alloyed and so potentially more susceptible to HICC. When the problem of heat-affected zone hydrogen cracking first became serious in the 1960s, national governments, for example in the UK, funded large research programmes to identify its causes and to develop algorithms for its avoidance. These led to standards such as BS 5135 and later EN 1011-2, which showed users how to solve the problem. Forty years later, appeals to European sources of funding for a similar project on weld metals failed, but a project involving Finland, Japan and the UK with Finnish government funding has recently been completed[13].

During deposition of a multi-layer weld, hydrogen continuously diffuses out of each weld bead. In principle, more hydrogen is lost at high interpass temperatures and long interpass times. However, in previous tests, low interpass temperatures had been achieved in the laboratory by waiting for the weld to cool naturally, that is by increasing the interpass time. In the new work, it was decided to vary the interpass time and temperature independently by cooling the welds, where necessary, with dry ice (solid CO_2).

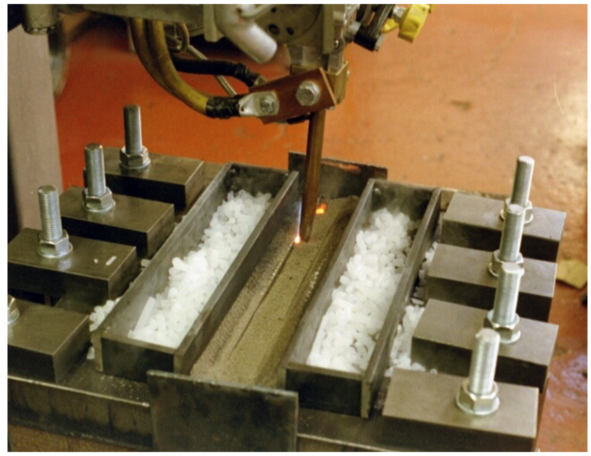


Figure 6(a) Groove preparation for multi-run HICC test (b) Welding for HICC test in progress

To generate stresses representative of real, highly restrained structures, welds were made in a 40 mm groove in 70 mm plate, rigidly clamped on to another plate of the same thickness, Figure 6. Special flux batches were made up to produce controlled deposited metal hydrogen levels between 3 and 20 ml/100g. Electrodes and wires giving weld metal yield strengths from 480 to 900 MPa were tested.

Interpass temperatures varied from 100 to 225°C. Interpass times were initially varied from 2 to 15 min, but since, surprisingly, this variable did not emerge as significant in the first series of tests, subsequent series were carried out with a fixed interpass time of 4 min. Heat inputs were 2, 3 and 4 or 5 kJ/mm.

The incidence of cracking was assessed visually, with transverse cracks appearing in the top weld beads after a delay period. Initially, cracking was assessed after 16 h as specified in EN 1011-2, but later it was found that in some cases, cracks first appeared later than this. The delay was extended to 7 days (168 h) for the remainder of the tests.

The interpretation of the results gave rise to much discussion, but one means of representing them, Fig 7, is easy to understand and is consistent with earlier diagrams.

As a broad guide, a diffusible hydrogen content of 5 ml/100g in a test to EN ISO 3690 should not give rise to cracking for weld metal hardness values up to 300 Hv. That value should be sufficient to allow X80 pipelines to be welded with overmatching weld metal, but hydrogen levels may need to be lowered further if overmatching is needed on X100 pipelines.

At least two investigations dealing with HICC have concluded that there exists for weld metals a certain hydrogen level, probably close to 3 ppm in the fused metal, above which the crack susceptibility is almost entirely dependent on strength or hardness, but below which microstructure becomes the controlling factor[14,15]. For welding manufacturers, this represents a challenge and an opportunity: the challenge to reduce hydrogen levels below this transition level, and the opportunity, having done so, to achieve high strengths without incurring further increases in crack susceptibility. Work has begun[15] on identifying desirable and undesirable

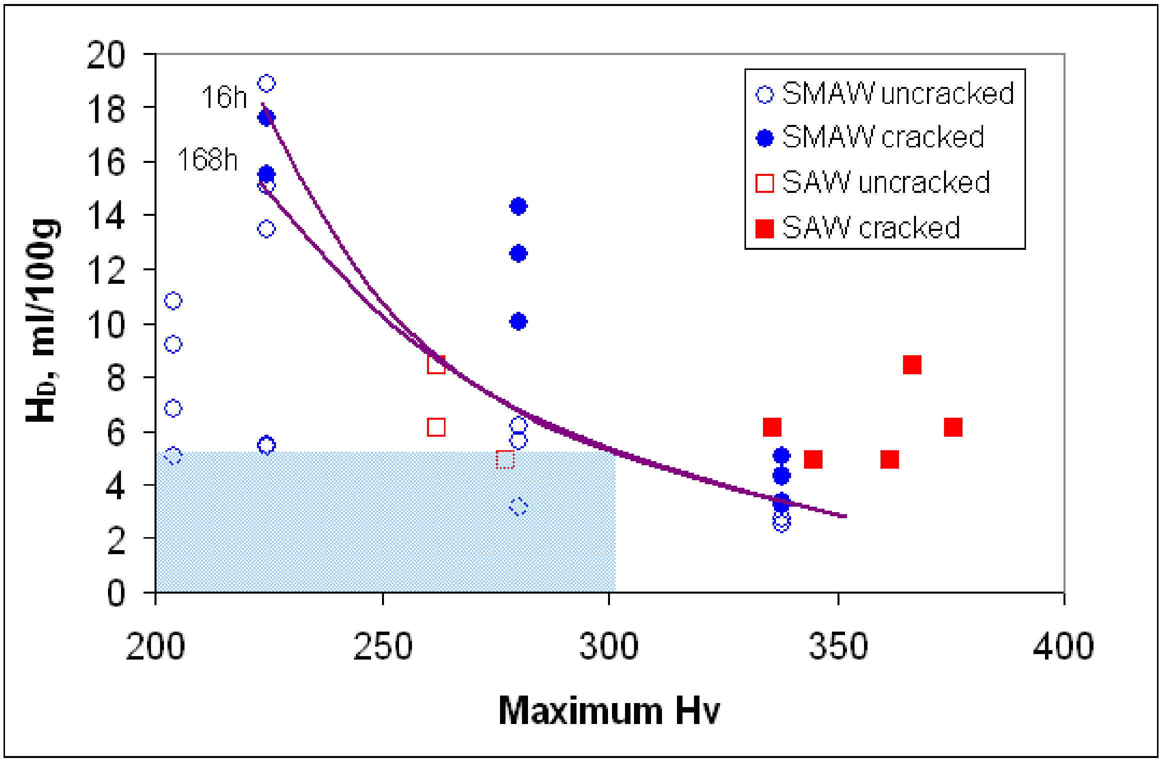


Figure 7. Crack – no crack boundary for SMAW and SAW welds in VTT programme.

microstructural components. Not surprisingly, acicular ferrite emerges as beneficial, but it was more unexpected that the intergranular martensite-austenite (M-A) constituent, which tends to increase as alloying rises in an attempt to increase strength, appears not to have an adverse effect on hydrogen embrittlement at these low hydrogen levels. It will be interesting to see what use manufacturers will be able to make of these insights in the years to come.

High energy-density processes

Whereas many of the above welding problems are related to the effect of high heat inputs and slow cooling rates on weld metals and HAZs, a group of high energy-density processes, especially beam processes such as laser welding, operate with lower heat inputs and faster cooling rates. These too can cause difficulties, particularly in the form of very hard structures with poor ductility and toughness.

When electron beam and laser welding were first introduced, their ability to penetrate relatively heavy sections without the need for beveled edges meant that many welds were made autogenously. Thus, not only was the cooling rate very fast, but the melted metal had the same composition as the parent material, with a very low oxygen content. Acicular ferrite was difficult to nucleate in the weld metal, which was therefore often highly martensitic.

In 1989, ESAB began formulating tubular wires for laser welding. Like the wires described above for pipe mill seam welding, these were designed to add calculated quantities of titanium oxides to the weld pool, thus facilitating the nucleation of acicular ferrite. The total volume of non-metallic material in the consumable remained below 1%. Results from an early version are shown in Fig 8. Autogenous welds gave poor toughness at temperatures below -40°C, which was associated with weld metal hardness of more than 400 Hv: the addition of a filler wire reduced the hardness by more than 50 points and improved both the level and consistency of the toughness. Furthermore, filler additions were found to increase the tolerance to fit-up and the resistance to porosity and solidification cracking.

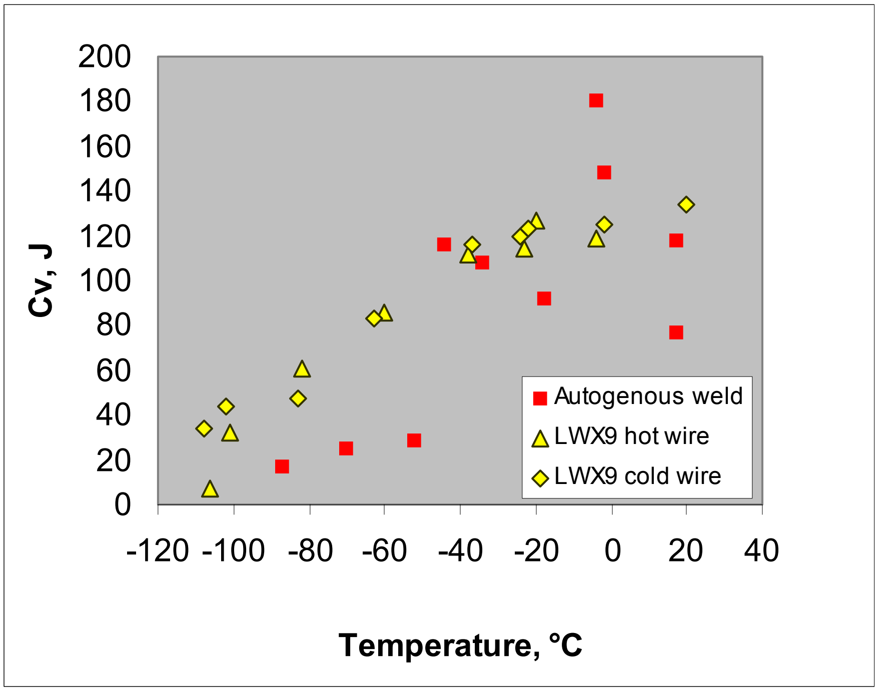


Figure 8. Effect of hot and cold filler wire additions on the toughness of laser welds in 12 mm plate

Over the next ten years, a series totaling almost 50 wires for laser welding was produced. These were tested in a number of research laboratories and many gave good results, but demand for the commercial supply of such products failed to materialise. Welding engineers had glimpsed the prospect of consumable-free welding, and the idea of reintroducing, not merely standard consumables but special tubular wires, did not appeal to them.

One way out of this impasse may be the use of hybrid laser welding for thicker sections. Here, a laser beam is combined with a gas-shielded metal arc process to gain the benefits of both. The laser gives improved penetration and welding speed, while the gas-shielded arc process gives better fit-up tolerance and a reduced weld cooling rate. This means that although a filler wire is needed, in most cases a conventional solid wire is adequate and the amount of wire needed remains less than for normal gas metal-arc welding. Pipeline contractors have already developed realistic procedures for hybrid laser welding of pipes, which will probably first be used on laybarges and for double jointing.

By chance, the technology developed for laser welding consumables has recently found an application in an area which does not at first seem related, namely hyperbaric welding. In fact, this resembles laser welding in two key aspects: the cooling rate is fast, with $\Delta T_{8\text{-}5}$ times typically in the range 2-4 s, and since a fully inert gas is used, the weld metal inclusion content with a solid wire is again insufficient to allow ready nucleation of acicular ferrite. In hyperbaric welding with solid wires, the toughness was once more inconsistent and often poor.

Experiments with wires developed for laser welding gave immediate improvements in toughness, with only some adjustment in the manganese and silicon levels being needed to meet the requirements of the user. Excellent charpy results are achieved down to –50°C at the initially targeted depths of 180-370m, while more limited tests show properties remaining good at simulated depths of 1600m (160 bar) and beyond[16].

In this case, there has been sufficient interest for a commercial product to be produced for hyperbaric welding. Since it is so close to those developed for laser welding, it may eventually find a use in laser welding where better than normal toughness is required. Indeed, samples have already been supplied for test to pipeline contractors and pipeline steel manufacturers.

Discussion

Forty years ago, a review of the the strengthening of steels by alloy additions[17] concluded: "In welding applications, the advantage of adding Nb and normalizing is that lower C and Mn contents may be employed, thus improving weldability and yet attaining greater yield strengths." In the intervening period, the replacement of major alloying elements with microalloying systems has, in conjunction with thermomechanical processing, revolutionised the welding of higher strength steels. When the Forties platforms were laid in the North Sea in the early 1970s, great savings were made because the maximum carbon equivalent value for the 75 mm thick steel was limited to 0.41. In particular, the carbon equivalent of pipeline steels has been driven down by the use of field welding practices which rely on very low heat inputs, often in conjunction with high hydrogen levels. This culminated in 2001 with the laying of a section of the Roma-Brisbane pipeline in Australia using X80 pipe welded with cellulosic electrodes.

In his 1979 John Player Lecture[18], the chief welding engineer of BP admonished the welding industry: "Welding has failed to keep pace with the improvements which have come about in the quality and variety of structural steels." In the years that followed, not only did welding consumables achieve unprecedented levels of strength, toughness and ease of handling, but the industry had to face and overcome new challenges set by the steel industry and by users' demands for continuing increases in productivity.

In the 1960s and 1970s, the steel industry developed a useful understanding of the mechanisms by which strength and toughness are developed. These were subsequently applied to welding consumables. With more acicular and highly dislocated microstructures, higher inclusion contents and different strain-hardening behaviour from wrought materials, weld metals needed new algorithms to predict their properties, but the underlying metallurgical principles remained the same and soon quantitative, predictive equations were available. By the 1990s, manufacturers were offering a complete range of arc welding consumables for welding steels with yield strengths up to 800 MPa or more, provided that heat inputs and dilution were suitably controlled.

Today, welding manufacturers face new constraints because users demand still leaner steels and higher productivity. For the first time, the tendency of dilution is to reduce, rather than increase, the weld metal strength: however, high dilution is often associated with high productivity. In the example described above, tests on an X80 steel with 0.045% C resulted in low weld metal yield strengths in high dilution submerged arc welds, but even since the tests were completed, a new paper[19] has described the development of an X80 material with a *maximum* of 0.04% C.

Manufacturers are tackling this problem from two directions. In the first place, process modifications such as synergic cold wire submerged arc welding and the replacement of solid wires with tubular wires aim to give users the productivity they seek while minimising any increase in heat input and dilution. Secondly, more robust weld compositions are being developed with higher total alloy contents. This involves an effort to understand new microstructural components and the way in which these affect strength and toughness. Welding manufacturers are increasingly working with steelmakers to ensure that weldability is evaluated at an early stage in steel development.

Hydrogen-induced cold cracking assumes increasing importance as steel strength increases and the burden of this falls mainly on the consumable manufacturer, since weld metals must rely on alloying rather than TMCP to develop their strength. Weld metal hydrogen contents have been reduced dramatically in the past twenty years, and will continue to fall. More interestingly, they are now arriving at a level where control of the microstructure will be able to reduce crack susceptibility at very high strengths.

High energy density processes, notably laser welding, are finally starting to make a serious impact on welding users and even the sometimes conservative pipeline industry. In this case, the fast cooling rates can lead to excessive hardness with low ductility and toughness in the weld. Here, manufacturers have anticipated the development by many years, and are ready with a battery of products developed for particular applications but never commercialised. However, a new wire for hyperbaric welding, based on these, is now available and may offer an alternative to bespoke wires.

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