State of the Art Review

Topical Report 278-T-01

For Project

Development of Optimized Welding Solutions for X100 Line Pipe Steel

Prepared for the

Design, Materials, and Construction Technical Committee of
Pipeline Research Council International, Inc.
Project MATH-1 Catalog No. L5XXXX
and

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety
Agreement Number DTPH56-07-T-000005

Prepared by
John Hammond

September 2011

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Catalog No. L5XXXX

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VALUE TO MEMBERS

The project, MATH-1 Welding of High Strength Steel Pipelines, was designed to fill the most critical gaps identified by PRCI members and industry specialists at the Pipeline Hazardous Material Safety Administration (PHMSA) 2006 Advanced Welding and Joining Technical Workshop, and to bring the necessary technology together for the practical use of high strength pipelines. From its inception, the project was intended to provide a fundamental understanding of factors that affect the mechanical properties of welds, as influenced by welding parameters. These issues are exacerbated in high strength steels, but are common for all pipe grades. In order to address the issues, the project has two focus areas:

- Focus Area 1. Update of Weld Design, Testing, and Assessment Procedures for High Strength Pipelines
- Focus Area 2. Development of Optimized Welding Solutions for X100 Line pipe Steel

Focus Area 1 set out to identify gaps in the current understanding of high strength line pipe and provide guidelines on the effective use of high strength line pipe from design and testing to weld integrity assessment procedures. Focus Area 2 set out to establish the range of viable welding options for X100 line pipe, including defining appropriate ranges for essential variables to ensure reliable and consistent mechanical performance, and to validate the performance through small and large scale tests.
MATH-1 consolidated the efforts and in-process results of several PRCI Board of Directors approved projects for 2007 in order to ensure that research efforts were coordinated and individual projects were not conducted in silos. Focus Area 1 incorporated

- MAT-4-1 Development of Supplemental Line Pipe Specification for High Performance Line Pipe
- MAT-6 Develop a recommended practice for measurement of weld tensile properties
- Focus Area 2 incorporated
- MAT-1 Development of Optimized Welding Solutions for High Strength Line Pipe
- MAT-12 Identify the cause and effect factors affecting the strength and toughness of welds and heat affected zones

The benefit of this consolidation was to ensure that technology development occurred in an informed, almost holistic manner. Having a single coordinated core research team addressing many of the interdependent issues involving the welding of high strength steel pipelines created synergies and depth in problem solving that would not likely have developed with the original independent project structure.
The benefit is in the technology that delivers solutions in key areas:

- Specifications for high strength line pipe properties, particularly tensile properties as related to grade classifications;
- Tensile test protocols for the reliable assessment of weld metal strength in narrow groove pipe welds;
- Small-specimen toughness test protocols for the assessment of weld metal and HAZ;
- Small-, medium, and large-scale tests that support pipeline design requirements;
- Weld integrity assessment procedures for various design requirements (stress- vs. strain-based design); and
- Optimized welding solutions for x100 line pipe steel.
-

Because full benefit is achieved through changes to applicable codes and standards, work product was developed in a manner to facilitate acceptance by codes and standards organizations.

The original intent was to conclude the project with a comprehensive report covering all aspects. As the core research team began to conclude the work, it became apparent that the large volume of information was best presented in a series of topical reports and one summary report for each focus area. The report organization is summarized as follows:

FINAL REPORT STRUCTURE

Focus Area 1 - Update of Weld Design, Testing, and Assessment Procedures for High Strength Pipelines		
Report #	**Description**	**Lead Authors**
277-T-01	Background of Linepipe Specifications	CRES/CANMET
277-T-02	Background of All-Weld Metal Tensile Test Protocol	CANMET/Lincoln
277-T-03	Development of Procedure for Low-Constraint Toughness Testing Using a Single-Specimen Technique	CANMET/CRES
277-T-04	Summary of Publications: Single-Edge Notched Tension SE(T) Tests	CANMET
277-T-05	Small Scale Tensile, Charpy V-Notch, and Fracture Toughness Tests	CANMET/NIST
277-T-06	Small Scale Low Constraint Fracture Toughness Test Results	CANMET/NIST
277-T-07	Small Scale Low Constraint Fracture Toughness Test Discussion and Analysis	CANMET/NIST
277-T-08	Summary of Mechanical Properties	CANMET
277-T-09	Curved Wide Plate Tests	NIST/CRES
277-T-10	Weld Strength Mismatch Requirements	CRES/CANMET
277-T-11	Curved Wide Plate Test Results and Transferability of Test Specimens	CRES/CANMET
277-S-01	Summary Report 277 Weld Design, Testing, and Assessment Procedures for High Strength Pipelines	CRES

Focus Area 2 - Development of Optimized Welding Solutions for X100 Linepipe Steel		
Report #	**Description**	**Lead Authors**
278-T-01	State of The Art Review	Lincoln
278-T-02	Material Selection, Welding and Weld Monitoring	Lincoln/CANMET
278-T-03	Microstructure and Hardness Characterization of Girth Welds	CANMET/Lincoln
278-T-04	Microstructure and Properties of Simulated Weld Metals	CANMET/Lincoln
278-T-05	Microstructure and Properties of Simulated Heat Affected Zones	CANMET/Lincoln
278-T-06	Essential Welding Variables	Lincoln/CANMET
278-T-07	Thermal Model for Welding Simulations	CRES/CANMET
278-T-08	Microstructure Model for Welding Simulations	CRES/CANMET
278-T-09	Application to Other Processes	Lincoln/CANMET
278-S-01	Summary Report 278 Development of Optimized Welding Solutions for X100 Line Pipe Steel	Lincoln

FOREWORD

The international gas industry is now developing gas fields in remote locations and has identified the need for cost effective methods for transportation or transmission of gas to market. In the last decade, this need has prompted the development of ultra-high strength line pipe steel which will be required for the economic construction of future long distance, high pressure gas pipelines. Until recently, the conventional limiting grade for such line pipe was American Petroleum Institute (API) 5L Grade X80 or its International Standards Organization (ISO) 3183 equivalent Grade L555 but joint private development programmes between oil/gas companies and major steel pipe manufacturers have resulted in new higher strength pipes; principally grades X90 (L625), X100 (L690) and X120 (L830). The steel makers and pipe mills have designed alloy compositions and pipe processing routes to optimise mechanical properties in the line pipe, including high toughness for fracture control for arctic use. Several oil and gas companies have conducted forming and girth welding trials on these new pipes together with extensive mechanical property evaluation and assessment of fracture arrest behaviour. Outline composition and properties of the new steels have recently been incorporated into leading international standards such as the 44th edition of API 5L, ISO 3183:2007 and CSA Z245-1. More recently other steel companies are known to have begun developments of similar higher strength steels for line pipe although such developments are currently at an early stage with little reported about the steels or experience of pipe manufacture or product evaluation. The first X90Q and X100Q smaller diameter seamless pipes have been developed and tested, albeit for a different intended application of deep-water sub-sea flow lines and risers. These steels have now been proposed and accepted for inclusion in future revisions of ISO 3183 and API 5L. Following the work by individual companies, PRCI recognised the need for a collaborative study, independent of single operator companies to take into account and supplement the earlier work in order to optimise the welding materials and parameters for field welding high strength line pipe and to demonstrate to the oil gas industry, their contractors and to regulatory authorities that this is a robust and reliable technology. This report is the first of a planned series and relates to PRCI Project Focus Area 2 (PHMSA Project 278), comprising a state of art review and gap analysis that is based entirely on publicly available information and such information as individual companies were willing to make publicly available.

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1. Introduction

The driving force for the development of high strength steel for pipelines is the prospect of significant reduction in capital expenditure (CAPEX) in the construction and commissioning of long distance gas pipelines. Further savings might be made by design optimization and lower operating expenditure (OPEX) leading to enhanced whole life economics for such pipelines. [1, 2, 3]

Over the past 40 years, pipelines have been constructed in almost the whole range of steel grades specified in the well known API Standard 5L ranging from grade A up to grade X80 (ISO 3183 Grade L555) and covering a range of specified minimum yield strength from 30 ksi (270 MPa) to 80 ksi (555 MPa).

In the case of major, large diameter oil and gas lines the trend during the 1980's/1990's was towards extensive use of modified grade X65 and later X70 and for a long time these were the workhorse materials of the industry. The use of X70 and then X80 was encouraged in mid 1980's by the availability of leaner composition steels in which the steelmaker developed an advantageous combination of strength and high toughness by thermo-mechanical controlled processing (TMCP) of steel plate for pipe. Such techniques, often involving accelerated cooling of the steels at the final stage of a carefully controlled thermo-mechanical rolling process, has succeeded in developing pipe having a uniform tough, fine grain, usually acicular ferrite microstructure throughout its wall thickness and simultaneously retaining a high weldability on account of the lean composition used.

The natural progression is for this technology to be applied further to stronger materials and several pipe manufacturers have been able to offer large diameter submerged arc welded pipe up to the X80 grade. Despite this, there were few well documented instances of gas lines being constructed in X80 grade in the early 1990's, although in the later 1980's Ruhrgas built an X80 gas pipeline in Germany, using submerged arc welded longitudinal seam (SAWL) pipe [4] and by 1994, X80 had become the standard 1067 mm (42 in.) and 1219 mm (48 in.) diameter pipe used by Nova in Canada. Despite the technology and materials being available for wider exploitation some time elapsed before other pipeline operators followed suit. By the mid 1990's, with the prospect of ultra long, high pressure gas trunk pipelines in remote areas, the thoughts of several companies turned to the possibility of pipelines constructed in even higher strength steels as a means of achieving major cost savings. A steel having a specified minimum yield strength of 100 ksi (690 MPa) was targeted and, by the late 1990's, several development heats of X100 steel had been cast and full size pre-production pipes manufactured for oil/gas industry evaluation. [5, 6, 7, 8, 9, 10, 11, 12]

It must be said that while large diameter X80 pipe could be viewed as an incremental development of the X65 and X70 technology, development of X100 was clearly perceived as step-out technology for the steelmaker, pipemill, designer, contractor and user alike. [4, 5, 6] X100 was not an established grade in API and no design rules or material performance characteristics had been specified or validated for X100. The work described in this report is the first attempt to fully characterize X100 prototype line pipe from four suppliers, to determine its weldability, to consider its influences on the design of pipelines together with design optimization and to determine its effects and implications on the construction of pipelines.

2. Current Knowledge and State of Material Development

2.1 Rationale for High Strength Pipelines

The primary field of application for high strength steel line pipe such as grades X90, X100 or X120 is envisaged as high pressure, large diameter pipelines for the transmission of dry natural gas, particularly for long distance systems**.** [1, 2, 3] In such pipelines, the economic advantages of such high strength steel can be exploited effectively in mechanical design and construction of the pipeline and in optimizing compression systems and operating costs. In this report the main focus will be on grade X100 (L690) which has been the most extensively developed and most widely reported but many technical factors and most conclusions could apply equally to grade X90 (L 630) which may merit serious consideration by some operators as an incremental increase from X80 (L555) which is already used extensively and it may open the possibility to a slightly wider supply source. Although grade X120 (L830) is also included in the study, it has been developed by one oil/gas company and, initially, by two major steel pipe companies. [13, 14, 15, 16, 17, 18, 19, 20] Although subsequent evaluation work appears to have been conducted thoroughly, including the development of welding wires and systems, little data was published until 2002 and supply sources remain few in number and contractor experience limited.

For large diameter long distance gas pipelines, the X100 line pipe will be mainly in the form of submerged arc welded (SAW) pipe of the UOE type, although the possibility of SAWH (helical/spiral) welded pipe cannot be ruled out particularly since at least one manufacturer of spiral welded pipe made a limited production run of Grade 690 spiral pipe which it is understood utilized a hot strip feedstock. (IPSCO, now Evraz), manufactured 2 km of NPS 42x12 mm pipe for TransCanada's Stittsville loop in 2006 and Fort Mackay in 2007. [21]

Although the primary driving force for this material is for gas transmission, there may be instances where it can be utilized elsewhere and its use in oil pipelines is a further possibility but at the present time with less economic advantage. At the present time, use of X100 with wet, corrosive streams where a high corrosion rate is anticipated, or where a heavy corrosion allowance is made is not envisaged.

At present no consideration has been given to using smaller or intermediate diameter X100 as high frequency welded (HFW) or electric resistance welded (ERW) pipe as firstly there is no current supply of these materials and no documented experience of hot strip feedstock production except for higher strength drill materials and casing (the so-called oil-country tubular goods OCTG).

Until recently, there has been no experience of X100 seamless pipe but, in the last 5 years two major companies have developed X90Q and X100Q seamless pipe with an intended application for deepwater high pressure flow lines, gas injection lines and risers. [22, 23, 24, 25, 26] The driver for this is that the relatively heavy scantling required of lower strength grades for this type of application can be reduced This is now being commercialized and at least one other seamless manufacturer has embarked on a similar development programme. Initial concerns that X100 seamless pipe would probably be a low production volume product, with higher chemistry and consequently lower weldability appear to have been overcome by utilizing a quench and temper technique.

Outside of the two above fields of application, there is presently no other rationale for specifying X90, X100 or X120 and since these products are relatively new to the market, any developer needs to undertake careful analysis of all technical aspects of the proposed pipeline project. In some cases, additional pre-project development will be necessary.

2.2 Onshore and Offshore Applications

2.2.1 Atlantic Seaboard X100 Pipeline (1960s)

The earliest reported application of X100 pipeline goes back to the 1960s when Atlantic Seaboard Corporation (subsidiary of Columbia Gas) laid a 914 mm x 6.4 mm (36 in. x 0.25 in.) pipeline as an 361 m (1185 foot) long test section which was employed as storage. [27] The material is understood to have been ordered as X100 to a former API Standard 5LU which was last re-published in 1980 and has since been withdrawn. Details of the pipe production are scant but the plate or strip from which the pipe was formed was quenched and tempered and manufactured by United States Steel Corporation. It is understood that field bending was carried out and that mechanized gas metal arc welding (GMAW) was used to manufacture the girth welds. It is also understood that there were some concerns about cathodic protection issues. The pipeline was hydrostatically tested at 88% of specified minimum yield strength (SMYS) with a 14 hour holding period and then operated for 12 months at 550 – 780 psig. It is reported that this section of X100 is still in operation approximately ~40 years later at pressure of 58% SMYS (800 psig) as part of an operating pipeline system following hydro-test with a 24 hour holding period at 110% SMYS. Although the developer's conclusion was that X100 was a feasible product for long distance gas pipelines no further interest was shown in the topic until the 1990's.
At the time of reporting, no purpose designed X90, X100 or X120 pipeline has been built and large scale experience has been of test sections of X100 built into expansions or loops of existing pipeline systems with the objective of proving welding, bending and pipelay techniques under practical site conditions, of large scale trials where several lengths of X100 or X120 pipe have been girth welded into test loops and buried into the ground for fracture control (burst) tests or as long term environmental test loops.

2.2.2 Saratoga - Westpath Project Pipelay - TransCanada PipeLines - September 2002

In September 2002, TransCanada PipeLines Ltd. (TCPL) undertook the first pipeline construction in the modern X100 pipe when a 1 km length of 1219 mm (48 in.) diameter x 14.3 mm wall thickness X100 manufactured by NKK Corporation (now JFE Steel Corporation) was installed at Saratoga, Alberta. [28, 29, 30, 31, 32, 33, 34] The pipe was specified to Canadian Standards Association (CSA) Z.245.1 Grade 690, supplemented with a TCPL purchase specification. Welding was carried out by a commercial contractor, Marine Construction Ltd, using CRC-Evans pulsed gas metal arc welding (GMAW-P) equipment. The root pass was deposited using a CRC-Evans 8 head internal welder and a Thyssen K-Nova welding wire (the same as used for welding X80 pipe). Hot passes, fill and cap passes were made by single wire GMAW-P using a CRC-Evans P260 tractor and an Oerlikon Carbofil NiMo-1 wire. Procedures were also qualified for repairs and for use of manual shielded metal arc welding (SMAW) techniques. The X100 welding was completed over a two day period and a few weld defects were successfully repaired. The X100 section was tied in to the main X80 pipe and the contractor was specifically trained in the refinement of techniques used for X100 as opposed to those used for X80. This trial pipelay proved that X100 could be welded and laid by a commercial contractor under site conditions but the early autumn weather could not be considered as a simulation for arctic pipelay in winter.

2.2.3 Godin Lake / Slave Lake Pipelay - TransCanada PipeLines Ltd - February 2004

In February 2004 TCPL proceeded with a second "demonstration" pipeline at Godin Lake/Slave Lake in Alberta, Canada. [28, 29, 30, 31, 32, 33, 34] This field test near Slave Lake in Alberta provided the three major sponsors TCPL, BP Exploration (BP) and ExxonMobil with a remote setting in which to demonstrate that X100 and X120 could be laid into a pipeline under normal winter site conditions. The field construction included a 2.0 km loop of 914 mm (36 in.) diameter x 13.2 mm wall thickness X100 pipe developed jointly by TCPL and BP and a 1.6 km loop of 914 mm (36-in.) x 16.4 mm X-120 pipe developed by ExxonMobil.

Girth welding of the X100 was entrusted to CRC-Evans, a subsidiary of CRC-Evans Pipeline International, who used a combination of conventional and tandem welding technology to complete the BP-sponsored loop of X-100 pipe. The tandem GMAW system developed for the pipeline welding industry by Cranfield University under sponsorship by BP and TCPL in the United Kingdom, almost doubles the welding speed of the conventional single-arc GMAW process. CRC-Evans used its P-600 welding systems to add the loop of X-100 pipe to the existing TransCanada line, and the computer-controlled P-600s achieved a lower-than-expected repair rate of 3.9%
.
Welding of ExxonMobil's sponsored X-120 loop marked the debut of a new CRC-Evans automated P-260 welding "bug" which utilized a new proprietary wire developed by ExxonMobil for welding X-120 pipe. At each girth weld pairs of computer-controlled P-260s carried GMAW-P welding torches. Four P-260 welding stations were employed during the four-day test, with crews completing an average of 41 welds a day with an overall repair rate of only 1.41 percent.

The field trials were judged a success with estimated welding production rates being achieved, both loops being completed at an extremely low repair rate. The field trials which duplicated actual working conditions, full scale X100 and X120 pipe, conventional contractors welding and laying pipe in a remote location during the severity of a Canadian winter provided confirmation of the field fabricabilty of X100 and X120.

2.2.4 Stittsville /Deux Rivieres Project - Eastern Mainline - TransCanada PipeLines Ltd July 2006

TCPL installed some 7 km of X100 line pipe in the Stittsville/Deux Rivieres Project. [32] The Stittsville loop included 5 km of 1067 mm (42 in.) diameter x 14.3 mm X100 SAWL pipe manufactured by JFE and 2 km of 1067 mm (42 in.) diameter x 12.7 mm X100 SAWH pipe manufactured by IPSCO (now Evraz Inc NA) of Regina, Canada The JFE pipe was produced to CSA Z245.1-02 Grade 690 [33] supplemented with a TCPL purchase specification and the IPSCO pipe to CSA Z245.1-02 Grade 690, also supplemented by TCPL. The pipelay contractor was Louisbourg Pipelines. The girth welding techniques were hybrid-tandem GMAW-P / single wire GMAW-P, again using CRC-Evans equipment. Root runs were deposited using an 8-head welder and Thyssen K-Nova wire. For the hot pass, fill and cap passes, a CRC-Evans P450 tractor which employs vertical and horizontal tracking was employed and a Thyssen NiMo80 filler wire was used. Repairs and tie-ins were covered by multiple procedures namely

- GMAW (ER480S-G) root and mechanized gas shielded flux cored arc welding (FCAW-G) (ESAB 15.09) fill and cap
- SMAW (E55010-G) root and hot pass with LHVD Böhler BVD 120 (E82518-G0 fill and cap

Three mechanized GMAW/FCAW-G welding stations were set up for tie-in operations and some tie-ins were completed using the SMAW procedure.

Some lack of fusion defects were reported at the 12:00 clock position and also at the 4:00/8:00 clock positions, the latter being attributed to the welder operator changing position in readiness for controlling welding at the bottom of the pipe.

This project provided a further site-based experience of welding X100 and of extending variants of welding processes.

2.2.5 Fort MacKay Project 2007 - TransCanada PipeLines Ltd [32]

This project has not been reported as extensively as others but utilized the Vermaat Technics single wire GMAW-P welding system. The contractor did not set up an extensive high production spread and used only one welding station due to the small amount of pipe. The pipe comprised 2 km of 762 mm (30 in.) diameter by 9.8 mm wall thickness IPSCO SAWH type, purchased to CSA Z245.1-02 Grade 690 with TCPL supplemental requirements. Root passes were made on to an internal backing bar and an Oerlikon Carbofil NiMo-1 wire was used with a tri-mix shielding gas. A Miller XMT 456 inverter power source was used. Only two tie-in welds were needed; one at each end of the section and these were made using a combination of GMAW/FCAW procedures. The same procedures were used for weld repairs.

2.2.6 Operational Trials of X100 at Spadeadam, UK - BP Exploration - 2006

BP Exploration commissioned an operational test at GL Noble Denton’s (formerly Advantica Technology) site in Spadeadam, Cumbria UK. [32, 35, 36] This comprised a buried 800 metre test loop of 1219 mm (48 in.) diameter X100 pipe complete with X100 cold bends, X80 induction bends and a forged equal tee. The X100 pipe was obtained from two suppliers; 0.4 km from Sumitomo and 0.4 km from Europipe and was manufactured to a specification based on API 5L with a BP supplement. The test section is coated and protected by a cathodic protection (CP) system and has been pressure cycled over a two year period to simulate a 40 year operational life of a high pressure pipeline.

The test section was constructed using conventional techniques for large diameter cross country pipelines and mainline girth weld root runs were made by Serimax using single wire GMAW-P and ESAB Autrod 13.25 wire under an Ar/CO2 shielding gas. For hot pass, fill and cap a tandem GMAW-P technique but using the same wire and gas was used. A variety of tie-in and repair procedures were qualified including a root welding procedure using semi-automatic GMAW with Lincoln STT® and a Lincoln Pipeliner®[1] 80 SG wire followed by semi-automatic FCAW-G utilizing an ESAB Tubrod 15.09 wire with an Ar/CO2 auxiliary gas shield.

At the time of preparing this report, the two-year environmental trial was nearing its end and a period of examination and analysis was expected to follow.

2.2.7 Snamprogetti-ENI Environmental Trial at CSM - Sardinia

A similar environmental-operational trial was conducted on X100 at CSM in Sardinia over a three year period for Snamprogetti-ENI; the project being called TAP (Transporto Gas al Alta Pressione). Operation includes typical pressure fluctuation over 18 months in order to assess pipe

[1] STT® and Pipeliner® are registered trademarks of Lincoln Global Inc., 1200 Monterey Pass Road, Monterey Park CA 91754.

susceptibility to Environmental Assisted Cracking (EAC) , accounting for different wall thickness usage factors (72% and 80% SMYS) as well as the presence of typical defects from third party interference. Although results of the trial do not appear to have been published, details of the manufacture of some of the pipes for the test installation have been reported by Europipe-Mannesmann. [37, 38]

2.2.8 Fracture Control (Burst) Tests

Several full-scale fracture control (burst) tests have been conducted on X100 in the last decade and possibly similar tests have been conducted on X120 but have not been published. Results of these tests generally remain proprietary to the sponsors and promoters of this work and their contractors. However, in summary, the following tests are known to have been carried out on X100.

a) Advantica Technologies - Spadeadam, UK. Joint Industry Project JIP 2001-2002 [39]
Two burst tests were carried out using lean composition gas on X100 pipe approximately 762 mm (30 in.) or 914 mm (36 in.) diameter supplied by Kawasaki Steel Corporation (now JFE), Sumitomo Corporation and Nippon Steel Corporation. Sponsors of this work were BP Exploration, British Gas, TCPL, and Alliance Pipelines.

The primary reason of conducting these tests was to obtain information on the fracture arrest capability of these materials and estimate the parent metal Charpy V-notch energy needed to guarantee arrest of a running fracture. Therefore, no attempt was made to simulate normal pipe welding techniques, the pre-requisite for girth welds being high integrity, defect free and therefore less likely to fail by diverting a running longitudinal fracture during the burst test.

b) Advantica Technologies - Spadeadam, UK. Joint Industry Project - BP Exploration Tests [36]
In August 2003 Advantica conducted a further fracture control test sponsored by BP Exploration on 1321 mm (52 in.) diameter thick wall X100 SAWL. The pipe was ordered to a simulated "arctic project" specification based on an extrapolation of API 5L (which at that time did not feature X100) that was supplemented by BP's requirements. The pipe was supplied by Nippon Steel Corporation. Again, the pre-requisite for girth welds was freedom from significant defects and virtually "zero-defects" at the 12 o'clock position that aligned with the horizontal plane along which the running fracture would be induced to start. This test was notable in that the test loop was pressurized with a rich composition gas, simulative of one possible commercial application.

c) Centro Svillupo Materiali (CSM) - "Demopipe" Fracture Control Tests - May 2002 [40, 41]
CSM conducted two or more "Demopipe" fracture control full-scale burst tests at their Perdas de Fogu test site in Sardinia. These have been reported within European Pipeline Research Group (EPRG) who were sponsors. The pipe was typically 762 mm (30 in.) diameter X100 manufactured by Europipe. Again, the principal reason for conducting these tests was to assess the running fracture behaviour of the X100 (under lean gas pressurization) and to estimate the Charpy toughness energy capable of arresting a running fracture in the material. Consequently, little has been reported about the girth welding of the test loop.

d) Other Burst Tests.
It is understood that some burst tests have been undertaken at The Force Institute in Denmark but in the form of a simple pressurized end sealed single pipe of X100 or X120 with the objective of establishing actual versus theoretical pressure at failure.

It is understood that CSM may have conducted confidential fracture control tests on X120 although no public reports are known.

In the above cases, girth welds are unlikely to be simulative of genuine pipelay welding.

2.3 Differences from Traditional Pipeline Applications

To date no pipeline has been designed from the outset to fully exploit the properties of X100 or X120 line pipe and the sections of pipeline laid using these grades of line pipe have all been as demonstrations that pipelines can be constructed and laid using conventional pipelay techniques. Therefore, in service, these sections of high strength pipeline are not operating at stresses of a similar level to those that would apply in a full economic exploitation of the materials.

The accepted field of application for X100 and X120 is for long distance large diameter trunk pipelines for gas transmission and, for scenarios such as the anticipated Alaska Gas Pipeline, the wall thickness of X100 would be in excess of 20 mm; thicker than any of the pipe used in the Canadian trials. However, the fact that BP's long-term environmental test uses 19.8 mm wall and it was welded using conventional mechanized GMAW-P indicates feasibility.

Within the last 40 years, there has been a progression from X65 gas pipelines in the 1960's/70's through to X70 in the 1970's through to the 1990's and, with the advent of TMCP, C-Mn micro-alloyed steel there was little metallurgical difference between the X65 and X70. Although X80 line pipe had been developed by a few pipe mills in the late 1980's, this grade was not widely used until Ruhrgas built an X80 SAWL pipeline in Germany in the mid 1990's [4, 5] and Nova Gas Transmission (now TCPL) laid pipelines using X80 SAWH and SAWL. However, the industry was slow to adopt X80 and only after 2000 did this grade begin to be used more extensively. In UK the gas industry (originally British Gas, then Transco and latterly National Grid) began to lay X80 pipelines, most of these being relatively short distance in-fills. The Grade X80 large diameter pipes can be considered as an incremental development of X70 with just minor changes to composition and with the plate for pipe forming being produced as low carbon, micro-alloy TMCP steel characterized by high yield strength, high yield to tensile ratio, good weldability and excellent toughness. When the user industry sought X100, the steel makers and pipe mills extended the X80 concept to its probable limit but typical compositions and method of manufacture can be seen as an extension of X80. X90 arrived merely as a default grade. The separate development of grade X120 pipe was a project devised by Exxon (now ExxonMobil) in concert with two leading pipe manufacturers, selected welding contractors and other institutions and was carried out in great secrecy leading to patented alloys. The first publication of data on X120 was not until 2002. It appears that X120 is not a further incremental step from X70, X80 and X100 as the metallurgy of the steel is different in that it is a boron steel. [14, 15]

Before a large diameter gas pipeline can be built in X100 or X120, the design codes need to be updated and this may require further test work for validation of specified requirements. The design rules in codes such as BS PD 8010 are based on three design classes; Class 1 being a pipeline in a location of low population density (< 2.5 persons/hectare) for which a design factor of 0.72 SMYS is permitted. For population densities greater than or equal to 2.5 persons/hectare, the pipeline location area is designated Class 2 where it may be extensively developed with residential properties, schools and shops or Class 3 in central areas of towns and cities with a high population and building density, multi-storey buildings, dense traffic and numerous underground services. In such locations the design factor drops to 0.30 SMYS unless, for Class 2 only, a risk analysis allows a higher factor to be used. These rules are probably empirical in origin but have stood the tests of time with a good safety record. However, they have not be validated for these new higher grade steels and their application to X80 may be an extrapolation of satisfactory performance in lower strength steels. Absence of validated design factors could be considered a technology gap with respect to X100 and X120. There are current moves within the pipeline operating industry to lift the 0.72 factor to 0.80 for some pipeline and for some future pipelines to be engineered on a basis of strain-based design. In considering such initiatives, the different shape of the tensile stress-strain curve in these new steels, including the value to be defined as yield strength needs careful evaluation. It is unlikely that X100 and X120 will be used in some European countries such as France or Belgium where historical technical directives by government agencies remain in place and restrict or prohibit the use of pipe materials with a yield/tensile ratio above 0.85 or 0.90.

The intended field of application for X100 and X120 is for long distance gas transmission pipelines and here again design rules e.g. IGEM/TD/1 *(Steel pipelines for high pressure gas transmission)* [42] and IGEM/TD/3 *(Steel and PE pipelines for gas distribution)* [43] deal with transmission of natural gas (predominantly methane) at a maximum allowable operating pressure (MAOP) not exceeding 100 bar (1450 psi) at temperatures between minus 25ºC and 120ºC. Firstly it is uncertain if rules have yet been validated for X100 or X120 and for pipelines operating outside the quoted temperature range, reference should be made to American Society of Mechanical Engineers (ASME) standard B.31.3 or British Standard (BS) 806 where design stresses for pipe materials at other temperatures are given. Unless such data exist for X100 or X120, there appears to be a knowledge gap for use of X100 or X120 in arctic environments where ambient temperatures can fall well below minus 25ºC and will influence the minimum design temperature (MDT).

Finally, for gas transmission, the designer needs knowledge of the fracture control characteristics of the pipe steel to be used. For the lower grades of pipe the Charpy toughness level required to arrest a running fracture in a gas pipeline is well documented from work by European Pipeline Research Group (EPRG) and by Battelle in USA. The original test work was on lower grades of pipe but has been extended and validated for pipe up to Grade X80 and now features as tables in standards such as EN 10208-02, ISO 3183:2007 and, for the first time, in the 44th edition of API Standards 5L. It is important to realize that the quoted values (for each of three design factors) relate to pipelines carrying lean composition, dry natural gas. The figures quoted in these standards do not include the newer high strength steels or for pipelines conveying rich composition gas and, at the present time, the only way of ascertaining if the pipeline material has adequate fracture arrest properties is to conduct a full scale burst tests. Several companies who have developed and tested X100 (and possibly X120) have now conducted such tests, although results remain proprietary and hence a technology gap exists until such data is in the public domain.

The operator companies involved with X100 or X120 have recognized that validation work has to be done to verify performance under specific site conditions, e.g. high strain due to frost heave or ground instability. So specific simulated tests have been conducted to determine the response of the materials to high longitudinal strain but results of such work are not yet in the public domain.

Therefore, there appear to be some gaps in the public knowledge or design standards relating to the use of X100 or X120 which could inhibit its full exploitation at present or which may cause regulators to seek further verification testing to supplement existing rules.

3. Pipeline Service Conditions

3.1 Design and Service Temperatures

Most pipelines operate within a temperature range of -25ºC to +120ºC and this fact is reflected in historical requirements of some design codes [42, 43, 44, 45, 46, 47]. Where pipelines are required to operate at more extreme temperatures the designer needs to make reference to specifications such as ASME B.31.3 or BS 806 from which design stresses for pipe materials at other temperatures are given. The data contained in these codes is again, long-term historical data from tests done many years ago. Some care may need to be exercised when using such data for other modern steels, which although described by a similar grade designation (e.g. X65) as a steel 30 years ago, may now be produced to a leaner composition by different steel processing and rolling techniques. Although properties may be similar over the normal temperature range care should be taken to verify properties at more extreme temperatures. Such codes have not yet been revised to incorporate data from newer steels such as X90, X100 or X120 and any operator or contractor intending to use such materials for pipeline construction may need to conduct tests at the extreme temperatures applicable to the design.

The minimum design temperature for an arctic (e.g. Alaska) gas pipeline may be as low as minus 23ºC based on lowest monthly mean environmental temperature and metal temperature experienced due to sudden, fast de-pressurization so verification of values of strength, toughness and ductility values for pipe such as X90, X100 and X120 becomes important. Despite the other extreme of ambient temperature for an X100 pipeline in an equatorial desert environment, the pipeline minimum design temperature may not be appreciably different if governed by fast depressurization. If these high strength steels are used for oil transportation, then minimum deign temperatures (MDT) will be governed to a greater extent by environmental temperature (also taking into account, the average temperature of the inventory) thus conferring a benefit on the MDT of an oil pipeline in a warm climate.

The fine grain microstructure of X100 produced by the TMCP process in a low carbon, lean alloy steel with controlled micro-alloy elements is an indicator that toughness should be maintained in parent metal at low temperatures such as minus 50ºC. However care must be taken to test longitudinal or helical seam weld metals where the strength development owes more to a higher level of alloying than in the parent steel. The phenomenon of heat affected zone (HAZ) softening [8] has been observed adjacent to seam welds in some X100 steels which calls for HAZ Charpy testing at the MDT, or preferably across a range of temperatures to determine transition curves.

Very different conditions apply for deep-water marine applications of X90Q and X100Q seamless pipe for flow lines, gas or water injection lines and steel catenary risers. In such cases a typical MDT for deep-water pipes could be 4ºC and the MDT for in-air sections will be governed by factors such as the minimum monthly mean temperature. Hence, for an environment such as the Gulf of Mexico for the in-air and splash zone sections of pipe might typically be 12ºC whilst sub-zero Celcius MDT might apply to similar installations in extreme northern or southern latitudes and in arctic conditions.

3.2 X100 Diameters and Thickness Ranges

The size range of X100 and X120 welded pipes produced to date is indicated in section 4.4 of this report and reflects the initial size ranges of interest of several companies for whom test pipes or preproduction pipes were manufactured.

Much of the X100 pipe produced to date is in the 762 – 1067 mm (30 - 42 in.) diameter range and with wall thicknesses between a general minimum of 12.0 mm and a maximum of 19.1 mm for SAWL type. This reflects the products supplied by the major manufacturers and could be taken to indicate significant manufacturing experience. [48] The trial runs of X100 pipe installed in the field in Canada typify this pipe diameter and thickness range. In the case of X100 SAWH pipe the wall thickness range supplied was at the lower end, typically 9.8 mm and 12.7 mm for 762 mm and 1067 mm (30 in. and 42 in.) diameter pipe respectively. If SAWH pipe is manufactured from continuous strip this may be a practical diameter/ thickness limit for this product although verbatim reports without further detail suggest that internal trials have proven manufacturing capability to around 25 mm thickness at one company.

Smaller quantities of larger diameter and higher wall thickness X100 have been manufactured to order and the top end of the diameter range includes 1219 mm and 1320 mm (48 in. and 52 in.) and wall thickness ranging typically from 14 - 20 mm. One manufacturer reported manufacturing 1420 mm (56 in.) diameter X100 pipe at 19 mm wall thickness. Also some X100 pipe has been manufactured up to 25 mm wall thickness.

All of the above have been manufactured from TMCP strip or plate and each strip or plate thickness range will be to a specific composition as it is unlikely that one composition would be suitable for all, even from a single manufacturer who may be able to vary TMCP cooling parameters. Therefore, pipe parent metal composition may vary with diameter and wall thickness of pipe and should be considered an essential variable to be taken into account when selecting girth welding consumables.

The situation concerning the X90Q and X100Q seamless pipe development is currently simpler as pipes of only one diameter (324 mm or 12.75 in.) two wall thicknesses (15 and 25 mm) and tightly specified chemical composition were manufactured and tested**.** [22, 23, 24, 25, 26] This implies that pipe composition is less of an essential variable at present and that selection of girth welding consumables should theoretically be simpler. However, this situation is likely to change as more sizes of pipe are produced and/or other manufacturers enter the market.

There is less information about the X120 pipe but substantial quantities of SAWL pipe are understood to have been manufactured at 914 mm (36 in.) diameter in wall thicknesses ranging from around 12 mm to 20 mm). Smaller quantities have been manufactured at 762 mm (30 in.) and up to 1219 mm (48 in.) typically at wall thickness also ranging from 14 to 20 mm. The X120 steel contains boron so it is uncertain if one composition base suffices for the above wall thickness ranges but, in the absence of such data, parent metal composition should be regarded as an essential variable. It is understood that a small amount of SAWH X120 pipe has been produced at 1067 mm (42 in.) diameter and 12.7 mm wall thickness.

3.3 Strength Range

The published strength ranges [49, 50] for X90, X100 and X120 are as shown in Table 3.1 below. The values specified relate to transverse direction tensile tests. i.e. the test specimen orientation being perpendicular to the longitudinal axis of the pipe and tangential to the diameter. It should be noted that the yield strength values that conventionally are measured as $R_{t0.5}$ for lower grades (up to L625/X90) are not used for L690/X100 and above where the $R_{p0.2}$ measurement applies.

(This was the result of study of available data by API Working Group 4193 when ISO 3183:2007 and 44th Edition of API 5L were drafted).

Table 3.1
Requirements for the results of tensile tests for PSL 2 pipe

Pipe grade	Pipe body of seamless and welded pipes						Weld seam of HFW, SAW, and COW pipes
	Yield strength $R_{t0,5}$ MPa (psi)		Tensile strength R_m MPa (psi)		Ratio $R_{t0,5}/R_m$	Elongation in 50 mm or 2 in A %	Tensile strength R_m MPa (psi)
	Min	Max	Min	Max	Max	Min	Min
L625M or X90M	625 (90,600)	775 (112,400)	695 (100,800)	915 (132,700)	0,95	a	695 (100,800)
L690M or X100M	690 (100,100)	840 (121,800)	760 (110,200)	990 (143,600)	0,97[b]	a	760 (110,200)
L830M or X120M	830 (120,400)	1 050 (152,300)	915 (132,700)	1 145 (166,100)	0,99[b]	a	915 (132,700)

a The specified minimum elongation expressed as percent and rounded to the nearest percent shall be determined using the equation and parameters provided in Table 7 of ISO 3183:2007 of the 44th Edition of API Specification 5L (2007).
b) Lower $R_{t0,5}/R_m$ ratio values may be specified by agreement for L690 (X100) and L830 (X120) pipe.

The implications of the yield strength range are important and, the range for X100 is wider than most users would prefer; a typical range of 690 - 810 MPa being preferable. However at the time the API and ISO standards were prepared, the pipe mills considered that the quoted ranges allowed economic manufacture without unacceptably high rejections due to out-of-specification maximum yield strength. The consequence for operator users and their contractors is the increased difficulty in selecting overmatching welding consumables for girth welding, particularly as much of the early welding procedure development work 51] had been on a basis of overmatching a yield strength of 810 MPa.

The following frequency distribution curve, Figure 3.1, is taken from X100 tensile data that is now several years old but indicated a wide spread of actual transverse direction yield strength data. [52, 53] On the basis of the results, 6% of the pipe would have been rejected for measured yield strength being marginally under the SMYS and, if the 810 MPa maximum YS criterion had been maintained, a further 6% would have been rejected as over-strength. Although a normal distribution curve has been drawn, the actual distribution can be seen to be tri-modal and suggests that at the time the pipes were produced, process control in rolling and/or pipe manufacture had not been optimised. It is recommended that further, more recent production data be evaluated to determine if a narrower distribution of yield strength can be obtained today. Consequently, any prospective girth weld consumable needs to offer a minimum yield strength of 840 MPa to guarantee to equal or overmatch the yield strength of the parent pipe in the transverse direction. This limits the choice of such consumables.

The tensile properties of X100 line pipe in the longitudinal direction are not specified in the API or ISO standards [49, 50] but are likely to be called up in a purchaser's supplementary specification and will need to be controlled tightly if the pipeline design will strain based. In such instances high strength in the parent pipe metal may be of secondary importance to achieving a high strain capacity in the longitudinal direction. It should be noted that the yield and tensile strengths in the longitudinal direction will be lower than for the transverse direction for SAWL pipe. The situation for SAWH or seamless pipe may be completely different and cannot be covered here from available data.

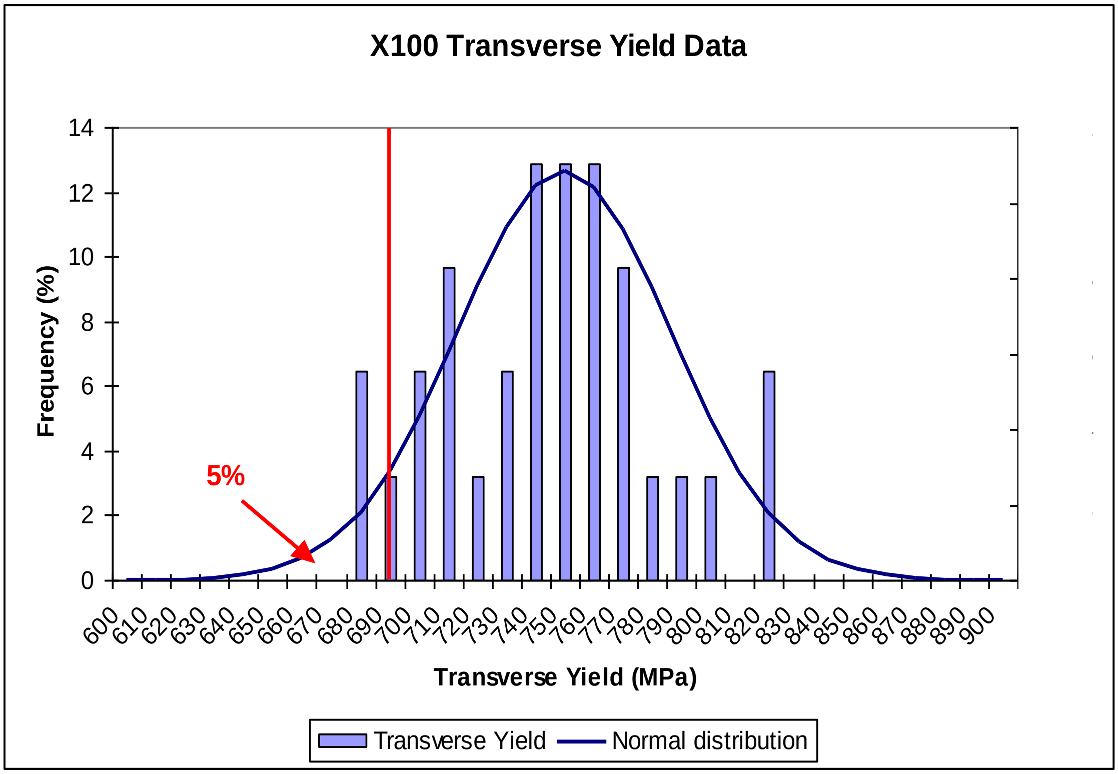

Figure 3.1 Distribution of Transverse Yield Strength in a Sample of X100

The frequency distribution curve for the strength in the transverse direction was taken from the same data and presented in Figure 3.2. Here again, there is a wide spread of actual yield strength values but the mode value is some 50 MPa less that that for the transverse direction. On the basis that the purchasers specified a minimum yield strength of 630 MPa in the longitudinal direction, the under-strength reject rate would have been less than 5%. Nevertheless, the wide distribution of individual yield strength values indicated that, at the time of purchase, the manufacturer still had some way to go to optimize rolling or pipe making controls.

A positive aspect is that any girth welding consumable selected to overmatch the transverse direction yield strength should comfortably overmatch the longitudinal yield strength which is an important parameter for strain based design, although strain capacity across the girth weld section will also be important.

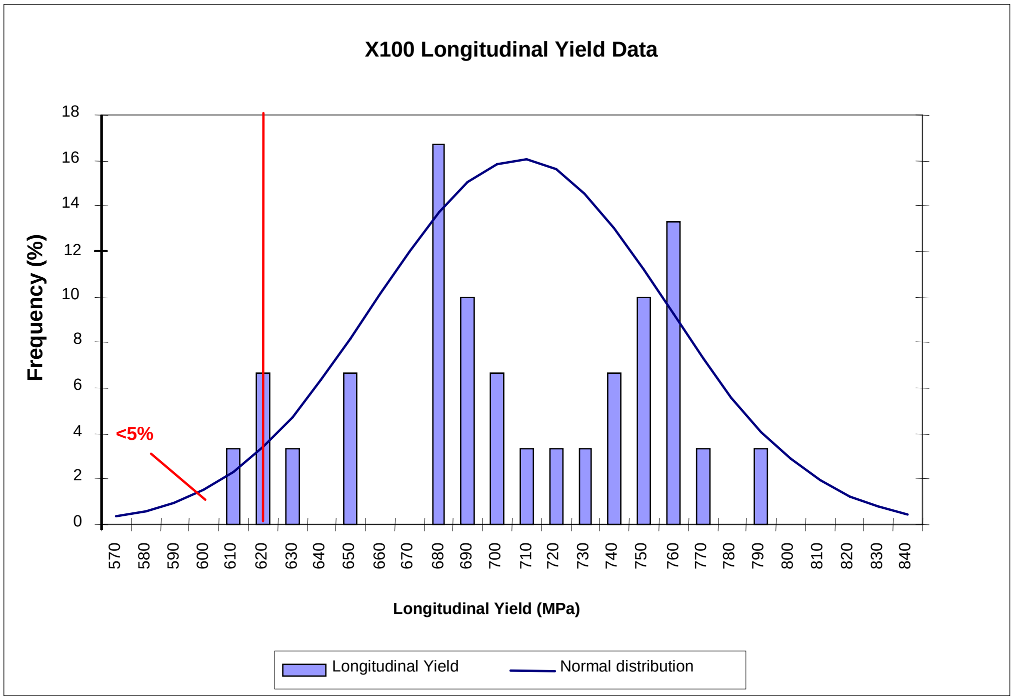

Figure 3.2 Distribution of Longitudinal Yield Strength in a Sample of X100

3.4 Anticipated Loading Conditions

Loading conditions are unique to each pipeline and, in addition to internal pressure, factors such as loads resulting in plastic strain of the line pipe during transport of line pipe and installation, residual stresses from welding and cold bending, dead weight from fittings, branches and appurtenances, possible loss of support from foundation shift, ground movement or seismic accelerations must also be considered in the design premise. Fatigue stresses may also arise due to expansion-contraction due to temperature fluctuations and, in gas pipelines due to pressure cycling (line-packing). The following points may be considered.

Buried Pipelines

- Axial strain due to ground foundation shift or landslip - needs high longitudinal strain capacity
- Slope instability resulting in foundation loss - may typically result in 1% strain
- Seismic accelerations which may typically result in up to 3% strain

Arctic Onshore Pipelines

- Axial and bending strain due to subsidence arising from melting permafrost
- Axial and bending strain due frost heave
- Combinations of the above
- Slope instability resulting in foundation removal
- Seismic accelerations
- Cyclic effects of any of the above

Arctic Marine - Sea and riverbed

- Bending strain and metal gouging from seabed ice scour by keels of floating ice
- Removal of or disruption of pipeline foundation by ice scour

- Permafrost thaw subsidence caused by higher pipeline temperature and pipeline deformation by overburden load.
- Strudel scour - removal of foundation by water currents, resulting in unsupported spans
- Upheaval buckling under longitudinal compression loading

In all of the above, detail of the uniform strain capacity of the X100 or X120 parent pipe particularly in the longitudinal but also in the transverse direction, is an essential parameter. Factors such as the strain capacity of the girth welds and heat affected zones together with the degree of yield strength overmatch must be ascertained to ensure that longitudinal strains are accommodated mainly within the pipe parent metal and not concentrated at the girth weld/HAZ junctions. Factors such as outer HAZ softening in X100 may also need to be taken into account.

Actual strain capacity data for X100 and X120 will be held by the companies involved in development of these materials but is not generally available. To intending users of these higher strength line pipe materials, detailed information on strain capacity remains a technology gap particularly where strain-based design is to be considered.

3.5 Anticipated Strain Capacity

Buried landlines may experience pipe deformation of ±1% strain or 0.35t/D for Level 1 (soil motion occurring once or twice during the pipeline lifetime) and ±3% strain for Level 2 (strong seismic motion which may result in soil liquefaction).

In marine pipelines uneven seabed conditions may result in plastic strain of the pipeline as it settles and conforms to the shape of the seabed. A plastic strain of 0.5% was considered for the Norwegian Haltenpipe project.

BP's small diameter Northstar Pipeline, laid in shallow water off North Slope, Alaska was designed with a maximum expected bending strain of about 1% from seabed ice gouging and about 1% for subsea permafrost thaw subsidence. [54] Upheaval buckling was prevented by the relatively low D/t ratio of 18 (resulting from small diameter thick wall X56 Q & T pipe for high toughness and high uniform elongation). The Northstar X56 material was different from X90 or X100, so the strain capacity of these higher grades should be evaluated.

The comparatively recent developments of X90Q and X100Q seamless pipe by Tenaris and Sumitomo will be of interest to the offshore industry (for which these materials were promoted). Again, for applications typified above detailed strain-capacity data is required by potential users.

3.6 Stress Based versus Strain Based Design

At the present time, there appears to be no genuine strain-based designed pipeline in X100 or X120.

Traditional design codes require pipelines to be designed on a limiting stress basis, which is a well-tried and generally conservative method in which the stress in the pipe wall is limited to a specific factor usually related to yield stress. Hence design to a criterion of 0.72 SMYS has been widely used for many years in the US and Western Europe, [52] although design criteria based on 0.8 have been the norm in Canada for many years. In areas where a higher safety factor is required, the allowable stress may be as low as 0.3 SMYS. The limiting stress needs to take into account installation stresses while the pipeline is in service.

Strain-based design may be considered when the limit of performance of the pipeline design cannot be adequately described in terms of stress and are better described in terms of strain under specified conditions. A high level of elastic strain and ultimately plastic strain may occur in pipe-lay situations such as reeling mainly of small diameter pipe (although reeling techniques are now used for larger diameters and for some higher strength steels). To date, no information is available about the reeling capability of X90Q or X100Q seamless (if used for subsea flow-lines).

Some land-based pipelines may experience loadings that take them beyond their capacity for longitudinal strain. One possible application for X100 and X120 pipe is for arctic pipelines e.g. an Alaska gas pipeline) in which unstable ground foundation (e.g. softening and subsidence of near-permafrost) may allow the pipeline to hog or sag. Frost heave on land or seabed ice scour in shallow arctic marine areas may force high strain movement in pipelines. Seismic loading and hillside slip on unstable slopes may also result in large strain movements of a pipeline.

3.7 Maintenance and Repair of X100 pipelines

It is uncertain how much consideration has been given to planning maintenance and repair of high strength pipelines in materials such as X100 and X120. To date the development work has centered on main line girth welding using predominantly mechanized GMAW or FCAW techniques for which the welding contractors have developed partial (cap and or weld body) and full penetration repair techniques to use in new construction. Techniques have also been developed for tie-in welds and welds of pipe to fittings which also include similar repair techniques for use in construction.

It is unknown at present if techniques have been developed to make repairs to these high strength pipelines while they are in service, e.g. welding of fittings or sleeves directly onto a line containing a fluid inventory and/or hot tapping operations. It seems unlikely that the procedures used in new construction would all be suitable for repair welding a damaged, (but emptied, purged and/or isolated) X100 pipeline that has had to be taken out of service. The reason for this is that the highly mechanized GMAW techniques have been custom designed for new construction and are not suited for repair techniques.

Conventional welding repair techniques for most pipelines (X70 and lower grades and perhaps X80) utilize manual SMAW. For some lower grade materials, cellulosic coated electrodes have been widely used, although use of such electrodes is not regarded as good practice on live pipelines due to their high hydrogen potential and the possibility of HAZ hardening in even low grade steel pipe under pressurized flowing conditions. Cellulosic-coated SMAW electrodes should not be used on materials such as X100. Where SMAW welding rods are considered they should be of the basic low-hydrogen coated type. However, there are relatively few suitable basic, low-hydrogen electrodes suitable for on-line welding of materials such as X100, thus necessitating careful selection of welding consumables and detailed development of any proposed repair procedure.

For repairs of line leakage or rupture, use of mechanical fittings (e.g. Plidco®[2] clamped type sleeve) as an interim or permanent repair is a possibility, however, development of suitable

[2] Plidco® is a registered trademark of Pipeline Development Company, The Corporation Ohio, 870 Canterbury Road, Cleveland OH 44145

welding techniques for attaching split tees to an X100 or X120 pipeline remains an probable technology gap.

Rules relating to normal hot-tapping procedures (which are generally empirically based) should not be considered conservative for higher strength steels as the local reduction in strength in zones under the weld pool may be proportionately greater than for lower grades of material and any calculations should be verified by test.

At the present time the availability of suitable fittings and flanges to match X100 or X120 is uncertain, so where fittings are required, the only practical recourse might be to specify X80 fittings with a thicker scantling attached to the pipeline with a transition weld.

4. Supply of X100 Material

4.1 History of X100 Development

Development of the modern X100 steels began in the mid 1990's with separate collaborations between steel makers and individual companies of the oil/gas user industry. Sumitomo Metals, Nippon Steel Corporation and Europipe collaborated with Shell Expro, BP Exploration and British Gas Technology, (later Advantica Technologies). All supplied prototype full size pipes. [8, 12] Sumitomo, Kawasaki Steel Corporation, NKK and Nippon Steel Corporation all later supplied some X100 pipe to Advantica Technologies for joint industry programme JIP fracture control (burst) tests. [39] NKK and Kawasaki Steel Corporation (now JFE Steel Corporation) collaborated with TCPL and, after merger as JFE Corporation, supplied pipe to TCPL for Westpath and Godin Lake Projects. [28, 29, 30, 31, 32, 33, 34, 35] JFE and IPSCO (now Evraz) collaborated with TCPL and supplied pipe for the Stittsville project. IPSCO (now Evraz) supplied pipe for the Fort MacKay project. [27] BP and TCPL jointly funded girth welding development work at Cranfield University UK, in which pipes from the above suppliers was used.

Responses to a survey for this project [48] by PRCI to known manufacturers of X100 and X120 can be summarized in Tables 4.1 and 4.2 as an indication of the timeline from concept design and trial heats of the steels to a capability to normal commercial manufacture of production pipe. At the time when manufacturers C and D indicated they would be prepared to manufacture commercially (in 2002 and 2003) respectively, it remained uncertain how high a production rate could be maintained and, if produced on the same lines as lower grade pipes in the pipe mills, how much production capacity would be turned over to manufacturer of the higher grades.

Table 4.1
Historical Development of Modern X100 (Year of Manufacture)

Manufacturer	A	B	C	D	E	F
Lab Trial Heats of X100	1985	1985	1996	1994	2005	2003
Prototype Commercial Manufacture of X100	2003	1999	2000	1995	2006	2005
Normal Commercial Manufacture of X100	-	-	2002	2003	-	-

Table 4.2
Historical Development of Modern X120 (Year of Manufacture)

Manufacturer	A	B	C	D	E	F
Lab Trial Heats of X120	1996	1997	N/A	2003	2005	-
Prototype Commercial Manufacture of X120	2001	-	2007	2004	-	-
Normal Commercial Manufacture of X120	-	-	-	-	-	-

The X120 development programme was funded and conducted, in some commercial secrecy, by Exxon (now ExxonMobil) initially with Sumitomo Metals and Nippon Steel Corporation and later with other selected suppliers and contractors. The first limited information relating to these projects was published in 2002/2003. [13, 14, 15, 16, 17, 18]

While most of the data relate to large diameter SAWL or SAWH pipes in Grades X100 and X120, data has also been included from one seamless line pipe manufacturer who has developed X90 and X100 seamless pipe via a quenched and tempered route. [22, 23, 24, 25] Since the time the survey was conducted, another manufacturer has developed similar Q & T seamless in the same grades and standardized requirements for these products will now be specified in revisions of ISO 3183 and API 5L

4.2 Current Knowledge - Parent Metal Composition

The X100 and X120 steel pipes made to date have been produced mainly by some of the world's premier steel groups and pipe mills and have been the subject of extensive and incremental technical development. In most cases manufacture has been exclusively by the basic oxygen steel making process followed by ladle treatments and vacuum degassing resulting in low carbon steel with micro-alloy additions and exceptionally low sulphur and phosphorus content. [7] However, the recently developed seamless X90 and X100 grades are made from electric furnace steel. [22, 23, 24, 25]

Each manufacturer's prototype X100 was developed to their own preferred compositions, suited to their own mill practice and subsequent plate rolling and pipe production. Much of the detailed information on X100 remains proprietary to each steel mill and, although this limits the amount of detailed data that is available to standardization bodies, the situation for X100 is really little different from that which has always been the case for lower grades of pipe such as X65, X70 and X80.

The consequence of different manufacturers offering a range of typical compositions to the standards working group inevitably results in the standardized composition limits being an "envelope" into which all or most X100 will fit. Clearly then, a situation of *caveat emptor* prevails and the purchaser of UHS pipe must judge factors such as the composition required, the ability of the steel maker to achieve the specified general mechanical properties and particularly any project specific property requirements such as low temperature Charpy impact or CTOD values, crack arrest properties and weldability in the final pipe.

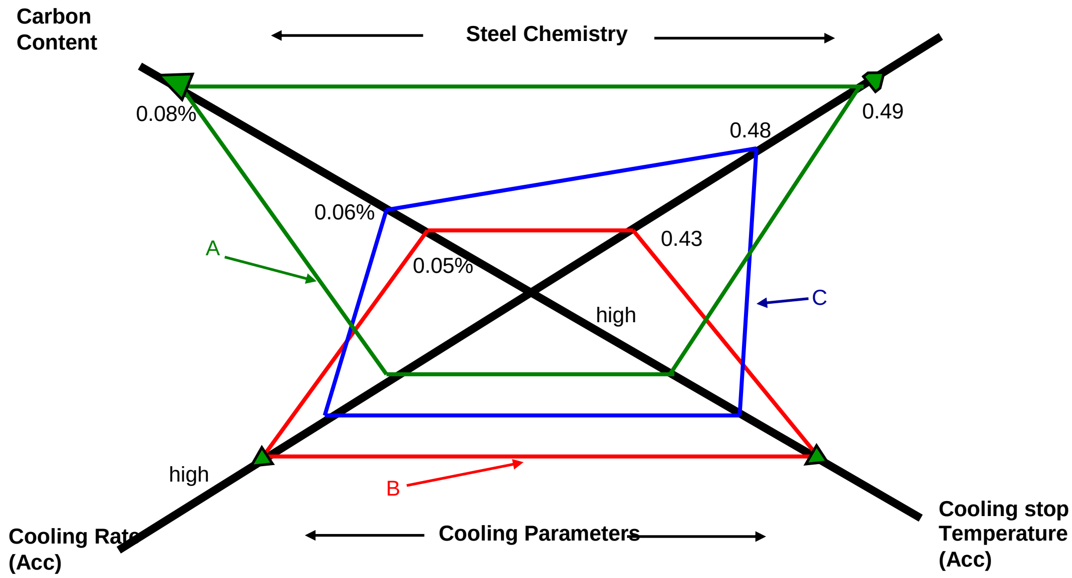

Figure 4.1. Carbon Content and Processing for UHS Pipe Steel
Acknowledgements. H-G. Hillenbrand & C. Kalwa, Europipe GmbH, Germany

The achievement of a range of tightly specified mechanical and physical properties depends on chemical composition of the steel and subsequent processing through steel making and secondary refining, plate rolling to tightly controlled parameters and the process of pipe manufacture itself. However, the fundamental start of the process is composition and the effects of varying composition have been demonstrated effectively in a diagram by Hillenbrand and Kalwa [56] Figure 4.1 which shows three approaches based on carbon content.

Approach "A" describes an alloy having a relatively high carbon content of typically 0.08% and a carbon equivalent value (CE) of 0.49. This is an easier composition for the steel maker to process as it allows X100 properties to develop in the plate at a low cooling rate and high accelerated cooling stop temperature. However, such a steel has the disadvantage of lower weldability and crack arrest toughness and is unlikely to achieve the required Charpy toughness at temperatures of typically minus 40ºC, as may be the case for an arctic gas transmission line.

Approach "B" utilizes a steel of lower carbon (typically 0.05% max) and a CE of typically 0.43. This would improve weldability but, to achieve the specified yield and tensile properties, fast cooling rates and very low accelerated cooling stop temperatures would be required. This creates a challenge for the plate rolling mill whose finishing procedures must be very tightly controlled. Such a steel may form martensite, toughness control becomes more difficult and HAZ softening may occur after welding the longitudinal seam.

Approach "C" utilises a medium carbon composition (typically 0.06%), resulting in a CE of 0.48%. This composition tends to optimise production flexibility, produces high levels of toughness and good field weldability.

4.3 Current Status of X100 Line Pipe

Table 4.3 summarises the generic alloying system used for X100 pipe and is based on responses to a PRCI questionnaire [48]**.** Individual manufacturer identities have been protected by assigning an alphabetic identifier in place of the company name and similarly, details of the generic alloying system have been reduced to carbon and manganese with typical percentages plus main alloy elements and micro-alloys usually without quantities. Some steel companies provided little information; others were informative. Manufacturers A through E are producers of large diameter pipe from plate or coil. Manufacturer F is a seamless pipe producer who uses the Q & T process and who has already placed considerable information openly in the public domain in support of an application to standardise X90Q and X100Q in API 5L and ISO 3183.

Review of the submitted data, shows that most X100 is produced to a 0.05-0.07% C, high Mn composition with varying amounts of other major alloy elements, typically Cu, Mo, Ni and in some instances Cr, with micro-alloy additions of Ti and NB and in one instance V. This establishes a generic X100 composition that will comply with the outline specification envelope of ISO 3183:2007 and 44th Edition of API 5L. This results in a parent metal CE_{IIW} value of typically 0.46-0.49, indicating that some preheat will be needed to weld these alloys and that hydrogen controlled welding procedures should be used. The Pcm values (which may be more appropriate for these low carbon steels) fall within the range 0.19 to 0.23. Despite the need for preheat, such values imply that the X100 steels will have good weldability.

One manufacture submitted data on a lower carbon variant of X100 with 0.03% C and similar manganese level but compensated with a higher level of conventional alloy. Despite the low C content, this results in a higher CE_{IIW} value of 0.6 but only a marginal increase in Pcm to 0.22. This suggests that Pcm may be a more reliable indicator of weldability for these steels than the conventional CE_{IIW}. This also suggests that this version of X100 steel does not fit into the Hillenbrand and Kalwa analysis explained in section 4.2 of this report.

Table 4.3
Generic Alloying System for X100 Line Pipe (Parent Metal)

Manufacturer	**Generic Alloying System (Alloy Element Weight % where quoted)**	**CE_{IIW}**	**Pcm**
A	0.06 C, 1.9 Mn, 0.04 Nb, 0.01Ti + other alloy 0.03 C, 1.9 Mn, 0.04 Nb, 0.01Ti + other alloy	0.46 0.60	0.19 0.22
B	0.06 C, 1.85 Mn + Cu, Mo, Ni alloy + Nb, Ti microalloy	0.49	0.20
C	0.05-.0.07 C, 1.8-2.0 Mn + Cu, Mo, Ni alloy + Nb, Ti microalloy	0.46	0.20
D	0.06-0.07 C, 1.8 - 2.0 Mo + Cu, Mo, Ni, Cr alloy + Nb, V, Ti microalloy*	0.47-0.49	0.20-0.21
E	Declared only as Nb+V microalloyed steel		
F	0.10 C, 1.25 Mn = Cu, Mo, Ni, Cr alloy + Nb, Ti microalloy**	0.54	0.24
G	Not declared		

* May contain controlled addition of boron ** Q & T seamless pipe

A similar tabulation of generic alloying systems used for X120 line pipe is shown in Table 4.4 again based on responses to the PRCI survey [48]**.** It should be noted that most manufacturers declared the intentional use of boron as an alloying element (which is significant versus X100 where boron is not intentionally added).

Table 4.4
Generic Alloying System for X120 Line Pipe (Parent Metal)

Manufacturer	Generic Alloying System (Alloy Element Weight % where quoted)	CE_{IIW}	Pcm
A	0.04 C, 1.9 Mn, 0.03 Nb, 0.03 Mo, 0.01Ti + B		0.21
B	0.04 C, 1.50 Mn + Cu, Mo, Ni alloy + Nb, Ti, V microalloy + Al + B	0.49	0.19
C	0.06 C- 1.9Mn. + Mo (no other elements declared)		0.22
D	0.06 C, 1.9 Mn + Cu, Mo, Ni, Cr alloy + Nb, V, Ti microalloy +Al +B	0.55	0.23
E	Declared only as Nb+B microalloyed steel		
F	Not applicable		
G	Not applicable		

4.4 Production Experience

Table 4.5 summarises the total production experience of X100 pipe of the major participant steelmakers and pipe mills to the end of 2007 again, as declared in response to the PRCI survey [48]. The total number of pipes produced includes early examples of simulated production pipe for evaluation purposes, some pipe produced for fracture control (burst), and some pipe installed in pipelines, as in Canada.

The estimate of production experience of X120 pipe shown in Table 4.6 is also based on limited survey data [48] but little is known about its use, particularly of the 690 pipes produced by manufacturer A. It is possible that such a large number many include early pre-production pipes for which composition or mechanical properties may vary from current X120.

Table 4.5
Estimate of X100 Pipe Production to 2007

Manufacturer	A	B	C	D	E	F
Total X100 Pipes Produced	100*	114	300	283	>300**	90
Type	SAWL	SAWL	SAWL	SAWL	SAWH	SMLS
Minimum Diameter (mm)	762	762	914	762	762	324
Maximum Diameter (mm)	1321	1220	1220	1420	1067	324
Min.Wall Thickness (mm)	14.0	12.7	13.2	12.5	9.8	15
Max Wall Thickness (mm)	25.0	20.6	18.4	25.4	12.7	25
Condition	TMCP	TMCP	TMCP	TMCP	TMCP	Q & T

* approximate number quoted by manufacturer
** Quoted as number of 12 metre long pipes or equivalent 150 double length pipes

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Table 4.6
Estimate of X120 Pipe Production to 2007

Manufacturer	A	B	C	D	E	F
Total X120 Pipes Produced	690	96	-	12	6	-
Type	SAWL	SAWL	-	SAWL	SAWH	-
Minimum Diameter (mm)	711	914	-	762	1067	-
Maximum Diameter (mm)	1220	914	-	762	1067	-
Min. Wall Thickness (mm)	12.0	16.0	-	16.1	12.7	-
Max. Wall Thickness (mm)	20.0	20.0	-	16.1	12.7	-
Condition	TMCP	TMCP	TMCP	TMCP	TMCP	

4.5 New Producers

Although the statistics furnished in the above tables relate mainly to the longest established developments of X100 and X120 as large diameter SAWL line pipe, there is evidence of a growing interest by other steel makers and pipe mills. Informal reports during the PRCI survey [48] indicated that steelmakers in China (possibly Nanjing/Julong) and South Korea were experimenting with X100 plate production for pipe manufacture. No reports have been received of other attempts to manufacture X120 pipe by other than manufacturers who have teamed up with ExxonMobil. No published information has been found until recently about current developments in China but it is assumed that the base steel alloy may be a low carbon, high niobium chemistry with controlled alloying with Mo, Ni and Cr and that the plate is produced as a form of TMCP. As this PRCI report neared completion, there was a need to find out more about the Chinese developments, particularly the wall thicknesses of rolled plate and the steel microstructure. However a recent report [57] within the steel manufacturing community indicated that Baosteel Group has produced a trial lot of X100 grade longitudinal submerged-arc welded (SAWL) pipes in 2011 at its UOE mill. The pipe is reported to be of outside diameter of 1219mm and a wall thickness of 23.5 mm and would represent the largest diameter and thickest X100 UOE-type pipes Chinese pipe makers have ever produced. It is understood that the trial will help the company to launch commercial production of X100 grade UOE pipes that may become substitutes for imported materials used by Chinese energy companies, especially China National Petroleum Corp which is about to start constructing the country’s third west-to-east natural gas pipeline.

As China accelerates installation of natural gas pipelines to meet its growing energy demands, it is understood that other steelmakers including Benxi Iron & Steel and Hunan Valin Xiangtan Iron & Steel have also developed X100 grade base materials for supply to domestic line pipe producers.

Beijing is encouraging the development of high-grade line pipes in order to reduce the country’s reliance on imported pipes and therefore lower construction costs associated with national natural gas projects

Baosteel’s 1,422mm UOE plant, located at its pipe works in eastern China’s Shanghai municipality, has a total capacity of 500,000 tonnes/year – comprising 400,000 t/y of line pipe (with grades up to X100) and 100,000 t/y of structural pipe. Plate feeds for the UOE plant come from Baosteel's 5,000mm-wide plate mill.

Limited information presented by the Korean steelmaker Posco [58] revealed that they have a plate development programme for both X80 and X100 tailored either for stress-based or strain-based performance at each strength level. It is unclear if X100 pipe has been manufactured in a genuine pipe mill or if properties have been measured on "simulated" pipe from the subject plate material

Enquiries made of VNIIST [59] indicated that there is no current development of X100 or X120 in the Russian Federation together with a policy that there is no perceived need for it. It was stated that considerable efforts are being dedicated to improving production, properties and use of a grade similar to X80 that is perceived to be the future workhorse material for long distance gas transmission pipelines in Russia.

Mill Constraints

Production and plant constraints applying to the manufacture of X100 in steelmakers and pipe mills may vary widely depending on each manufacturer. Furthermore the constraints may not be fully understood by all purchaser-operators wishing to order X100 grade line pipe and, as the need for this high strength material becomes more widespread, additional steel-makers and pipe mills may be encouraged to enter the market. At the time of the early development of X100 (circa 1990's) it was felt that the first producers may have been constrained by limitations of plant or production capacity although the pioneer companies have probably addressed any such constraints in the interim period with plant upgrades, process improvements and customisation. The manufacturing technology of these mills will have benefited from the early development experience and production runs. The following possible constraints may apply to more recent entrants to the market.

- Steelmaking - This is unlikely to be a major constraint although newcomers may need to go through iterations of composition, making adjustments to optimize composition, process and properties of the steel. Variation of base steel composition may result in the need to modify hot rolling practices for plate.
- Casting - Unlikely to be a major constraint unless the continuous caster and slab sizes are too small too permit sufficient rolling reduction in the finished plate thickness.
- Plate rolling - This may be a constraint for some mills depending on the force and hot-rolling characteristics of the plate mill (or plate mill train) and limits on incremental reduction per pass required to optimise rolling from slab to finish thickness.
- Cooling rate through the plate rolling process - This may be a constraint particularly if a mill has no accelerated cooling capacity capable of delivering thermo-mechanical controlled processed (TMCP) condition in the finish-rolled plate.
- Pipe making - Possible constraints on plate forming, including press-breaking (crimping of edges), U and O forming due to limited press power or power/force limitations of pyramid rolling machines (for larger diameters) or helical forming machines in SAWH pipe mills.
- Welding - Submerged arc welding technology and welding consumables selection for longitudinal seam welds in SAWL pipe or helical seam welds in SAWH pipe may be a constraint unless the mill has proved welding by development trials. Incorrect or non-optimized welding consumables may result in inferior seam weld mechanical properties, unacceptable hardness levels, possible extensive HAZ degradation and subsequent field welding difficulties at the girth weld/seam weld interface. SAW wires for seam welding are generally more highly alloyed than X100 base material and may typically contain up

to 2% Ni and other alloys and/or additions of boron. The high SAW heat input levels and multi (tandem) wire arrangements necessary to make the internal and external seam welds in SAWL pipe can result in extensive heat affected zones with some HAZ softening adjacent to the weld seam. Conversely, if a pipe mills is forced to make the pipe seam welds using more than one internal and external pass, the process will be costly and will impact the overall economics of X100 supply.

- Expansion - Pressure limitations of expanders for UOE pipe or end-sizing expanders (if used) for other pipe may be a production constraint for some mills if the power of the cold expander is insufficient to impart a sizing strain of up to 0.015. This might not be a problem for thinner wall X100 pipe but limitations could be reached for thicker wall pipes where expanders had been designed for a maximum grade of X80 and would only be overcome by upgrading of existing facilities or installation of new and more powerful plant.
- Production Speed - Production of X100 line pipe may be slower than for lower grades of pipe if the higher material strength requires slower pressing or rolling techniques or if seam welding using high heat input multi-wire submerged arc welding has to be completed in more passes to limit heat affected zone softening or if expander capacity is insufficient for the normal expanded lengths, necessitating smaller "bites" for expansion. Any of the foregoing situations may create production bottle necks, the effects of which would have to be factored into the price.
- Dimensions - Diameter and wall thickness constraints may apply but in most cases this would be merely a further restriction of the diameter/thickness combinations that an individual mill can manufacture for other grades of pipe up to X80 (L555).
- Mechanical Properties - Production of yield and tensile strength within the specified minimum and maximum specified limits and acceptable yield to ultimate tensile ratios may prove challenging for some pipe mills particularly when required with high specified values of Charpy energy for gas pipelines. Again, this constraint may simply be an extension of a similar situation with lower strength pipe such as X80 or X70 (L555 or L485).

The probability of one or more of the above constraints existing applies to each potential X100 order, irrespective of the manufacturer. Since the purchase specification for most X100 pipe will extensively supplement the base requirements of L690 (X100) specified in ISO 3183, API 5L or CSA Z245.1, the purchaser may need to prequalify selected steel and pipe mills to ensure they can comply and, for most orders, require manufacturing procedure qualification as specified in Annex B of ISO 3183 and API 5L or equivalent company or national specifications.

4.6 Bends and Fittings

Most development programmes to date have not addressed the question of bends and fittings for X100, yet for high strength steel pipelines, the specification, design, supply of bends and fittings is a necessary pre-requisite.

These items fall into two separate categories that may be treated differently. The first are items of substantially the same diameter or nominal wall thickness as the pipeline itself, typically tees or reducers which will form part of the main pipeline but which may be produced from plate or a "mother pipe" whilst the second category may be items produced as forgings, typically flanges or weld-o-lets or heavier section sweep-o-lets which may be fabricated from heavier gauge plate.

In the case of items such as bends or tees, the designer is faced with the options of specifying the item with equivalent X100 properties which, at present, will necessarily involve dialogue between purchaser and manufacturer to agree the technical specification, actual chemical composition range, manufacturing route, guaranteed dimensional tolerances and minimum mechanical properties.

Induction bends could be produced from mother pipe made to similar chemical composition as the X100 line pipe, or, where necessary, by additional alloying to withstand the induction heating and quenching cycle and subsequent tempering. The latter may be necessary as it is unlikely that the induction bending process will result in the same TMCP treatment that produces the X100 mechanical properties in pipes. Mother pipes for bends are usually thicker section than the comparable line pipe to provide a margin for extrados thinning during induction bending and this alone usually requires the small additional alloying to guarantee the minimum specified mechanical properties throughout the section. The implication for this in fabrication and pipelay welding is inferior weldability and such items may therefore require higher preheat for welding.

A further point requiring specific attention is the response of the longitudinal weld metal to induction bending. Although this issue has long been proven and qualified for lower strength induction bends up to X70 and possibly for X80, it appears not to be addressed yet for X100 except in one trial conducted by Sumitomo Metal Industries in collaboration with Dai-Ichi High Frequency Co. Ltd. [60] Collaborative programmes between purchaser, pipe mill and induction bender will be needed to investigate and resolve this issue.

One important factor to consider in producing an X100 induction bend is the condition and mechanical properties of the tangent ends. In some lower grade pipe bends the induction bent section is left in the quenched condition while the tangent ends remain unheated during the process and are supplied in the condition in which the parent pipe was manufactured. This implies that there is a microstructural transition within the HAZ between the bend section and tangent end but, as long as the mechanical properties of the letter are compatible to those of the line pipe in which the field joint will be made, no significant problems exist. For higher strength induction bends the completed bend can be tempered in a heat treatment furnace but some minor microstructural differences may remain between the bend and tangents ends. In the case of the highest strength materials it is suggested that the entire bend should be quenched and tempered to ensure uniform microstructure and mechanical properties throughout. The technique for this remains open to interpretation; one variant being the use of extra long tangent ends along which the induction coil and quench ring could be passed without bending to reproduce the thermal cycle of the induction bending process. The other option is to subject the completed bend item to a separate quench and tempering process although care will be required to maintain dimensional stability.

Fabricated bends may be handled somewhat differently as these are can be press-formed as half shells from plate and welded together. This also requires detailed technical dialogue between the purchasing and supplying parties. Technical aspects to consider will be plate chemistry and, although plates with the requisite mechanical properties can be produced, typically by the quenched and tempered route, the impact of any heating above the Ac1 temperature for forming or even above the tempering temperature on the microstructure and properties must be evaluated.

An alternative process of leaving the final (quality) heat treatment until after pressing and welding of the bends would also requires evaluation with particular attention to weld metal which may not be amenable to subsequent quench and temper treatments. A variant of this process would be to hot-press the half shells which could then be quenched and tempered before welding, followed by a stress relief treatment. Cold pressing of half shells for pipeline of this strength would not be advocated.

The use of “cut and shut”, cut and weld, cold formed bends (other than as permitted in field bending) or wrinkle bends is not recommended for X100.

Technical issues surrounding the fabrication of items such as tees or reducers are much the same as for fabricated bends and the solutions for one may be equally applicable to the other. An alternative approach that may be adopted for this class of fitting is to design the items in lower grade material e.g. X70 or X80 but with a substantially thicker scantling, which is the technique already used widely in the manufacture of tees, where mechanical compensation is required for material removed from the main to form the branch. This would generally maintain acceptable weldability although some alloy increase above nominal may be needed for exceptional thickness. This could marginally affect field weldability, although it is not unusual for items such as these to be welded in to the pipeline using low-hydrogen tie-in procedures rather than by stove-pipe or by mechanized GMAW as used for the main line. Where an X80 induction bend forms part of an X100 pipeline, the weld between the line pipe and bend assembly will usually from the strength transition. Generally there will be a requirement to match the bore of the pipe and bend so the additional wall thickness will be on the OD of the bend and tangent ends may be tapered down to avoid undesirable girth weld profiles. Such tapering could result in a short length of under strength material in the tangent ends. Palliatives might include either finite element analysis of typical weld joint or using a high strength girth weld to bridge the thickness transition. This type of detail merits further studies to find an optimized solution.

For fittings such as flanges, weld-o-lets and forged bends dialogue with suppliers is again needed to ascertain the preferred technical specifications and options for manufacturing as these are not yet standard items. In the case of flanges, code considerations concerning design may require attention, so simply thickening the scantling (particularly of the flange face) may not be an option. However, for trunk pipelines, flanges are used mainly in compressor or pumping stations or terminals. One suggested option in such areas is to utilize existing grades of flange materials such as X70 or perhaps X80 of suitable size and with a thickness transition between the (thicker) weld neck and thinner X100 line pipe.

To obviate the difficulties of welding such items in the field, the option of pupping them with appropriate X100 pups at manufacture might be considered. Similar design and construction issues must be considered for valves, in which the valve bodies and weld necks or flanged connections must be seen as mechanically compatible with X100.

Technical issues with smaller items such as weld-o-lets are generally simpler as these items are small thick wall forgings, already heavily mechanically compensated. It is suggested that manufacturers be contacted for their specific recommendations where such items are required for X100. One option would be to specify alloy composition and heat treatment (such as Q & T) capable of producing the X100 yield strength with requisite tensile strength and toughness. i.e. similar to the technique used to manufacture X100Q seamless pipe. Some existing compositions of parent forgings may already be adequate for this purpose, the principal variation then being only heat treatment. The alternative of a more highly alloyed forging is probably acceptable in the case of small fittings as such items are usually easily preheated to higher temperatures, can be welded with basic low hydrogen processes and the main limitation may be if post-weld heat treatment is needed to temper the HAZ of the fitting alone. Some on-site techniques exist to do this. In some instances, existing proprietary fittings may already be suitable for use on X100 pipelines but this would require further study.

A development of X100 bends by Sumitomo Metal Industries and Dai-Ichi High Frequency in Japan has been reported at an ISOPE 2007 Conference in Portugal.[60] A 3DR 90° induction bend was produced from 914 mm (36 in.) x 16.0 mm wall thickness X100 mother pipe having a carbon equivalent value of 0.52 and Pcm of 0.20. A major challenge was the selection of seam welding materials to produce a composition that would be amenable to quenching from the induction forming and then subsequent tempering. Although consideration was given to weld metals containing boron, the optimized combination of strength and toughness was ultimately obtained with a low carbon, boron-free weld deposit containing unspecified amounts of Cu, Cr, Ni, Mo, Nb, V and Ti alloy. The oxygen content of the weld metal was controlled carefully and carbon equivalent values were 0.55 and 0.58 respectively for the outside and inside seam welds. The key technology appeared to be in selecting an optimum austenisation temperature from which to quench, cooling rate from quenching and specifying an optimum tempering temperature of 400°C based on the results on Charpy energy temper-response trials. The total bends, including both tangent ends were quenched and tempered. The net result was that the target tensile properties in the intrados, extrados and neutral axis were comfortably met or exceeded e.g. yield strength > 690 MPa and tensile strength > 758 MPa in the transverse direction. The transverse yield strength of the bend mother pipe was reported as only 650 MPa and it is unclear if, after quenching and tempering, the transverse yield strength of the tangent ends of the bend was of similar magnitude to the values of the bend portion. Charpy tests resulted in high absorbed energy values ranging from 250 J to over 300 J in the parent material at test temperatures of -20°C and -30°C while in the seam weld metal values ranging between 100 J and 150 J were more typical. Fusion line/HAZ Charpy values were also less than for the parent metal ranging typically from 90 J up to 190 J. Surface hardness values appeared to be generally acceptable in parent and weld metal but could marginally exceed 300 HV10 a the intrados and extrados surface. The trial proved the feasibility of producing an X100 induction bend with an acceptable combination of properties at 16 mm thick but further trail work would be needed to prove materials and techniques for X100 bends in thicker wall pipe. The metallurgical design of the mother pipe is considered key to obtaining a satisfactory induction bend.

Induction bends in X80 grade material were manufactured in Europe and used in one operational trial of X100. The bends were induction pulled to a 5D bend radius leaving 1 metre tangent ends. Three 45º bends and one 22.5º bend were manufactured and the bore of the tangent end was sized to match the nominal ID of the X100 trial pipe. The wall thickness of the X100 test pipe was 19.8 mm and that of the X80 bend was 27.5 mm so in practical terms, the outside diameter of the bends was 15 mm greater than the 1219 mm (48 in.) OD of the pipe. Although the CE_{IIW} of 0.49 and Pcm of 0.22 of the X80 bends were similar to the corresponding values for the X100 pipe, some differences in composition were noted, the bends having a marginally higher contents of carbon, molybdenum and niobium and a controlled addition of vanadium.

There have been no reports of manufacture of other X100 full diameter line pipe fittings such as equal tees so this remains a technology gap. An equal tee in X65 grade was manufactured for one operational trial by rolling and forming from over-thickness plate and being supplied in the quenched and tempered condition. Clearly the outside diameter of such a tee will be considerably greater than that of the X100 pipe and it is unclear how the thickness transition is managed. Further work to develop X100 fittings of this type appears to be needed.

5. Specification of X100 Material

5.1 Standards and Specifications

The earliest specification of X100 was in API Specification 5LU and related to the Atlantic Seaboard pipeline material produced from quenched and tempered strip. [27] Since this material and its method of production have not been replicated in the modern X100 and, as API Specification 5LU was withdrawn in the early 1980's, the material and its associated standard may be considered as of historical interest only.

Grades X90, X100 and X120 (ISO Grades L625, L690 and L830) featured for the first time in the editions of ISO 3183:2007 [49] and the 44th edition of API 5L [50] published in March and October of 2007 respectively. Leading steel makers, pipe mills and major oil/gas industry companies co-operated to specify limits of chemical composition summarised in Table 5.1 and mechanical properties in the earlier Table 3.1. At present, the standards restrict these grades to welded PSL 2 pipes in which the parent plate of strip is in the TMCP condition and the grades carry an M suffix in their designation. Theoretically, there is no reason why production of plates by a quenched and tempered process could not be used except that the dual heat treatment cycle would be uneconomic compared with TMCP. However, recent application has been made via API/ISO to standardise a quenched and tempered smaller diameter seamless X90Q and X100 type of pipe for sub-sea applications. If successful, these grades could be standardised as seamless in the next revision of ISO 3183 (probably 3183:2012) and the 45th edition of API Specification 5L.

In the present standards, the chemical composition limits are, in common with the limits for lower grades, set widely and the selection of micro-alloy element systems is left to the steel maker subject to overall total limits for Nb, V and Ti to no more than 0.015%. Further controls are exercised in respect of maximum limits for Cu (0.50%), Ni (1.00%), Cr (0.05%) and Mo (0.05%) which allows individual steel makers to exploit their own favoured alloy systems. In the case of X100 and X120, there is a maximum permissible limit for boron of 0.004% but, in the case of most X100, purchasers' supplementary specifications are likely to seek elimination of boron above the detectable limit of 0.0005%. This is not the case for X120 steel which relies on a controlled level of boron for development of strength and it is alleged to limit the extent of softening in the seam weld HAZ.

Table 5.1
Composition of High Strength Line Pipe Specified in ISO DIS 3183:2010
(Revision of ISO 3183:2007 and 44th edition of API 5L)

Steel grade (Steel name)	**Mass fraction, based upon heat and product analyses** % maximum									**Carbon equivalent** [a] % maximum	
	C	**Si**	**Mn**	**P**	**S**	**V**	**Nb**	**Ti**	**Other**	**CE_{IIW}**	**CE_{Pcm}**
Seamless and welded pipes											
L625Q or X90Q	0,16	0,45	1,90	0,020	0,010	b	b	b	c, e	as agreed	
L690Q or X100Q	0,16	0,45	1,90	0,020	0,010	b	b	b	c, e	as agreed	
Welded pipe											
L625M or X90M	0,10	0,55	2,10	0,020	0,010	b	b	b	d , f	—	0,25
L690M or X100M	0,10	0,55	2,10	0,020	0,010	b	b	b	d, c		0,25
L830M or X120M	0,10	0,55	2,10	0,020	0,010	b	b	b	d, c		0,25

a) CE_{IIW} applies where C ≥ 0.12%. CE_{Pcm} applies where C ≤ 0,12%
b) Unless otherwise agreed Nb+V+Ti ≤ 0.15%
c) 0.004% maximum for B
d) unless otherwise agreed Cu < 0.50%, Ni , 1.00%, Cr < 0.50%, Mo < 0.5%
e) unless otherwise agreed Cu < 0.50%, Ni , 1.00%, Cr < 0.55%, Mo < 0.8%
f) No intentional addition of B

The API and ISO working groups, when finalising the compositional limits, deliberately declined to set Carbon Equivalent (CE) values for the new steels which are of lower carbon content but more micro-alloyed than the steels used for the development of the IIW CE formula. However, a maximum CE Pcm value of 0.25 is assigned to each grade as the CE Pcm formula was developed by Ito and Bessyo [61] , on lower carbon steels. It is argued that the blanket CE_{IIW} of 0.43 and CE Pcm of 0.25 applied to all PSL 2 grades of pipe in Table 5 of the API/ISO standard is insufficiently discriminating as most pipes can be produced to lower values of CE_{IIW} and Pcm.

Mechanical properties for these new PSL pipe grades are specified in Table 7 of the ISO / API standard and include minimum and maximum limits for yield and tensile strength and, for the first time in API 5L, a limit on yield to tensile ratio *($R_{t0.5}/R_m$)*.. These required much negotiation with pipe manufacturers being reluctant to accept lower value than the 0.95 (for X90/L625), 0.97 (for X100/ L690) and 0.99 (for X120/L830). A footnote caveat for X100 and X120 allows lower values to be specified “by agreement”.

The approach to Charpy testing of all grades of pipe in the 44th edition of API 5L /ISO 3183:2007 is for the minimum required CVN to increase with grade and diameter of pipe. Hence for small diameter pipe, e.g. 508 mm (20 in.) only 27 Joules is required for grades X60 through X70 while a minimum of 40 Joules is required for pipe of the same size in grades X70 through X120. At the other extreme of diameter e.g. 1422 mm (56 in.) through 2134 mm (84 in.) the 40 Joules minimum is specified for only X60 pipe and rises incrementally to a minimum of 95 Joules for X100 and 108 joules for X120. These values are required for transverse direction test pieces tested at 0ºC, or if agreed, at a lower test temperature. These values might provide a reasonable guarantee against brittle fracture at the test temperature but, in the case of higher strength steel, large diameter pipe above grade X80 (L555) will not provide adequate guarantee against running ductile fracture. To determine the level of toughness necessary to arrest a running ductile fracture in X90, X100 or X120 it is necessary at present to conduct fracture control (burst) tests as the necessary data based on Charpy values is not yet available. The results of early tests suggest that the parent pipe toughness required to arrest a running ductile fracture may not be consistently achieved in production pipe and, for some applications, crack arrestors may be required. Annex G of API 5L and ISO 3183:2007 gives further guidance.

The only other widely used standard to include Grade X100 (as Grade 690) is the Canadian Standard CSA Z245.1. [33] (This standard was published in September 2002 and updated in August 2005). A recent revision, published as CSA Z245. 1-07 in April 2007 has included Grade X120 (as Grade 825 rather than grade 830). The approach taken by CSA is markedly different to that of the API and ISO standards in that the chemical composition table is simplified to the same overall compositional envelope for all grades from 215 through to 690. This gives little guidance to the ultimate user but allows the steelmaker and pipemill to manufacture to their own preferred limits within an overall compositional envelope. Large oil/gas companies and their contractors will probably negotiate specific limits with manufacturers possibly via detailed supplementary purchase specifications. Obtaining smaller quantities of pipe from distributors may however be a riskier business. An attribute of the Z245.1 system is that a maximum carbon equivalent limit of 0.40 is imposed (c.f. the 0.43 of the API/ISO standard) and the CE is calculated by a more demanding formula than the CE_{IIW}. CSA Z.245 utilizes the Yurioka CEN carbon equivalent formula [62] and takes into account the additional elements of Si, Nb and B with appropriate factors and the whole equation is multiplied by a compliance factor F which depends on the carbon content of the steel. A further positive factor is that clause 4.2.1 of this standard requires all pipe furnished in accordance with the standard to be weldable to procedures in accordance with CSA Standard Z.662. [63]

CSA Z.245.1-06 specifies mechanical properties for Grades 625–825, summarised as follows in Table 5.2.

In conclusion, the ISO, API and CSA standards provide a useful base for specifying X90, X100 and X120 but, at the present time, purchaser supplementary specifications are needed to ensure such pipes are fit for the intended purpose.

Table 5.2
Mechanical Properties for Grades 620 (X90), 690 (X100) and 825 (X120) as specified in CSA Z245. 1-06

Grade	Min YS MPa	Max YS MPa	Min TS MPa	Max TS MPa	YS/TS max[a)]	YS/TS max[b)]	El %
620	620	760	690	900	0.93	0.95	12-19*
690	690	825	760	970	0.93	0.97	11-17*
825	825	1050	915	1145	0.99	0.99	9-15*

a) Flattened strap specimen
b) Specimen other than flattened strap
c) Elongation is dependent on test piece dimensions

5.2 User Supplementary Specifications

Until ISO 3183:2007 [49] and the 44th edition of API 5L [50] were published in 2007, most X90, X100 and X120 pipe would have been ordered to purchaser's specifications supplementary to the 42nd or 43rd editions of API 5L, using X80 as a benchmark. An exception to this was Canadian orders of Gr 690 (X100) where a TCPL engineering specification with supplementary requirements to CSA Z245-1 was used. [64] Even now, with an ISO/API standard covering base requirements for X90, X100 and X120, these materials will generally be purchased as a mill order rather than from stock and will be customised for each particular project using a unique supplementary specification. It is common practice in oil and gas companies to utilise a pipeline data sheet specifying essential requirements and confirming minimum and maximum design temperatures from which the Charpy and Drop-Weight Tear (DWT) test temperatures are derived. The following are given as examples of items likely to be covered in a purchaser supplement.

- Weldability data - demonstrate that the (X90 thru X120) material is field weldable at the diameter and wall thickness ordered or within an agreed diameter/wall thickness range.
- Requirements for Manufacturing Procedure Qualification Tests (MPQT) in which pre-production or "first-off" production pipe is intensively tested to qualify the Manufacturing Procedure Specification (MPS). Changes to production parameters outwith agreed tolerances may trigger the need to re-qualify the MPS.
- Confirmation of the processes of steelmaking, any secondary refining and casting techniques and slab surface inspection before rolling.
- Inspection and treatments of rolled plate such as agreed edge shearing and UT of plate body and edges to a recognised standard such as ISO 12094 (Grade E2 for edges and B1 for plate body). It should be noted that rolling technology is usually proprietary to the steel mill and may not be subject to supplementary specification, although the may seek assurance of consistency through the mill's own QA procedures.
- The supplementary specification may require the manufacturer to nominate a preferred or restricted (heat and product composition) within an "envelope" range typical of those of API 5L or ISO 3183.
- Typically limiting CE_{IIW} and CE Pcm values [65] may be specified to tighter limits than in API 5L or ISO 3183 as shown in Table 5.3.

Table 5.3
Typical supplementary Carbon Equivalent Limits for X90 and X100

Pipe	CE_{IIW}	CE Pcm
X90	0.48 max	0.22 max
X100	0.51 max	0.22 max

- Specifying the type and direction of tensile tests and properties to be measured as typically shown in Table 5.4. e.g.
  - Transverse direction tensile tests on round bar
  - Longitudinal direction tensile tests on flattened strap or round bar
  - Transverse direction flattened strap - results for information and comparison
  - Measurement of the value of uniform elongation (uEl) from all tensile tests for strain based designs.

Table 5.4
Supplementary transverse and longitudinal tensile test requirements

Grade	Yield Strength Minimum		Yield Strength Maximum		UTS Minimum		UTS Maximum		Elongation on 50.8 mm or 2 in. GL
	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	%
X90 T	90	620	108	745	100	690	125	862	a*
X90 L	85	586	102	705	100	690	125	862	a*
X100 T	100	690	117	810	110	760	130	900	a*
X100 L	90	620	105	720	100	690	130	900	a*

a The specified minimum elongation expressed as percent and rounded to the nearest percent shall be determined using the equation and parameters provided in Table 7 of ISO 3183:2007 of the 44th Edition of API Specification 5L (2007).

- Specification of maximum yield to tensile ratios (mandatory for the transverse direction) and for information in the longitudinal direction typically Table 5.5) with consideration for test specimen, as flattened strap test pieces tend to return lower results than round-bar test pieces.
- Fracture toughness (Charpy testing and test temperature)

Table 5.5
Yield/Tensile Ratios for X90 and X100

Grade	$R_{t0.5}$/Rm (transverse)	$R_{t0.5}$/Rm (longitudinal)
X90	0.93	0.93
X100	0.95	0.95

5.3 Characterisation of X100 Linepipe

5.3.1 Composition

A major characterisation of X100 line pipe was conducted on early (pre-production) SAWL pipes as part of a Joint Industry Programme (JIP) undertaken by Shell Global Solutions, BP Amoco and BG Technology. The total study which was reported at a conference in 2000 [8, 9, 10, 11, 12] included extensive microstructural and mechanical characterisation of the pipes provided by four major manufacturers and associated studies conducted as part of the same JIP. These studies provided an initial benchmark and, although further developments and improvements of X100 have taken place since (and will have been subject to characterisation studies by individual companies) there has probably been less open publishing of results than for these initial trials. The details of this JIP dealing with weldability, damage and defect tolerance, and cost optimisation studies are provided later in this report (Section 6).

Parent pipes were produced as TMCP (controlled-rolled, accelerated-cooled) plates, two of which received a subsequent tempering treatment following accelerated cooling which would probably no longer be representative of current production. All pipes were manufactured by UO press-forming, longitudinally submerged-arc welding by standard multi-wire mill-pipe welding machines from both OD and ID and final expanding; the so-called UOE process. The chemical composition of the pipe base metals was published in 2000 [8] and is reproduced here as Table 5.6

Table 5.6
Chemical composition of early pre-production pipes (circa 1996)

	Pipe A	Pipe B	Pipe C	Pipe D
C	0.07	0.05	0.08	0.07
Si	0.09	0.23	0.26	0.29
Mn	1.80	1.94	1.86	1.73
P	0.004	0.008	0.010	0.003
S	0.002	< 0.003	< 0.002	< 0.002
Al	0.046	< 0.003	0.046	0.046
Cu	0.29	0.17	0.24	0.22
Cr	0.16	< 0.01	0.03	0.04
Ni	0.51	0.42	0.21	0.20
Mo	0.21	0.10	0.27	0.22
V	< 0.002	< 0.003	< 0.002	0.040
Ti	0.011	0.008	0.015	0.014
Nb	0.048	0.040	0.047	0.037
Ca	< 0.0003	< 0.0050	0.0015	< 0.0003
N	0.0035	0.0023	0.0034	0.0041
B	< 0.0003	< 0.0003	< 0.0003	< 0.0003
CE_{IIW}	0.498	0.435	0.480	0.446
Pcm	0.210	0.179	0.218	0.203

All pipes chemistries were based on low C - Mn based with Mo additions to increase the strength of the steel. Further deliberate additions varied per manufacturer namely:

- Pipe A: additions of Cu, Cr, Ni and Nb, resulting in a CE of 0.498 and a Pcm of 0.210
- Pipe B: additions of Ni, Cu, Ti and Nb resulting in respectively a CE of 0.435 and a Pcm of 0.179
- Pipe C: additions of Cu, Ni, Ti and Nb giving a CE of 0.480 and a Pcm of 0.218
- Pipe D: additions of Ni, Cu, Ti and Nb, which gave a CE of 0.45 and a Pcm of 0.203

The alloy content of the seam weld metals of pipes A, B and D were much higher than the parent metal and this is reflected in significantly higher CE values shown in Table 5.7 for these weld metals. Pipe C contained weld metal with a comparable CE value as the base metal. It is important to realize that although much fundamental work was performed on these pipes and they were the forerunners of later developments, characterization revealed some deficiencies that had to be eradicated by later improvements.

Table 5.7
Carbon equivalent values for the seam weld metal

	Pipe A	Pipe B	Pipe C	Pipe D
CE inside	0.617	0.566	0.487	0.639
CE outside	0.601	0.608	0.485	0.644

5.3.2 Characterizing Microstructure

The Shell workers examined the microstructures of the base metals at mid-thickness and show photomicrographs in their published paper. [8] A comparison of the microstructures of the base metal and the double sided SAW seam weld is summarized in Table 5.8 from which it was concluded that the differences in microstructure of the base metals reflects the effect of the differences in chemistry in combination with the manufacturing route of the plate. Although the detail refers to a early examples, the same procedure is necessary to characterize each production of high strength pipe such as X100 or other grades.

Table 5.8
Summary of Microstructures of Early X100 Line Pipe

Pipe	Base Metal	Weld Metal	Coarse Grain HAZ	Fine Grain HAZ
Pipe A	Polygonal ferrite and bainite; Grain size ASTM 10/11 slightly finer near surface. No segregation	Predominantly acicular ferrite with some bainite	Relatively coarse aligned ferrite with MAC and bainite. Grain size ASTM 5	Very fine polygonal ferrite with some MAC constituents and bainite
Pipe B	Fine grain bainite. No segregation	Predominantly acicular ferrite with some bainite	Relatively coarse aligned ferrite with MAC and bainite. Grain size ASTM 4	Very fine polygonal ferrite with some MAC constituents and bainite
Pipe C	Fine grain bainite with some patches of martensite. No segregation	Predominantly acicular ferrite with some MAC constituents	Mixture of relatively coarse aligned ferrite with MAC. Grain size ASTM 5	Very fine polygonal ferrite with some MAC constituents and bainite
Pipe D	Polygonal ferrite and bainite; Grain size ASTM 11, Slightly smaller near surface. Weak segregation zone	Predominantly acicular ferrite with some bainite	Mixture of aligned side plate ferrite with MAC and bainite. Grain size ASTM 5	Predominently polygonal ferrite and bainite

5.3.3 Characterizing Hardness

Most pipeline construction codes specify maximum hardness limits for weld metal and/or parent hardness which, in the case of higher strength grades of line pipe, may result in requirements that are difficult to achieve. The same holds true for the seam welds in welded pipe. In the case of lean composition, TMCP steels, a tendency also exists for HAZ softening in some materials: a phenomenon that is exacerbated by the high heat-input multi-wire SAW processes utilized in pipe manufacture. The systematic hardness examinations conducted by Shell are typical of procedures required to characterize other new line pipe.

A summary of the average and maximum hardness results (Hv10) for both the pipe base metals and the seam welds is given Table 5.9 which was given in the original paper. [8] Some additional observations per manufacturer are highlighted below:

- Pipes A and B: The weld metal was slightly harder than the base metal but with softening of the HAZ and a gradual decrease in hardness from the base metal towards the HAZ.
- Pipe C: Weld metal hardness was similar to the base metal but almost no softening in the HAZ. Hardness increased in the transition between the fine grain HAZ towards the unaffected base metal.
- Pipe D: The weld metal was significantly harder than the base metal but significant HAZ softening.

Table 5.9
Characteristic Hardness of Early X100 Line Pipe

Pipe/position	Average Hardness HV10			
	Base metal (BM)	**Transition BM to HAZ**	**GC HAZ**	**Weld metal**
Pipe A	259 (274)		258 (273)	
external wall		248 (253)		281 (288)
centre		263 (277)		301 (311)
internal wall		262 (274)		305 (323)
Pipe B	266 (279)		245 (280)	267 (274)
external wall		237 (245)		278 (283)
centre		239 (259)		276 (287)
internal wall		239 (243)		
Pipe C	260 (272)		260 (282)	
external wall		256 (262) (296*)		262 (270)
centre		271 (286)		270 (288)
internal wall		257 (270) (281*)		264 (274)
Pipe D	279 (300)		262 (300)	
external wall		243 (250)		304 (314)
centre		255 (267)		314 (326)
internal wall		266 (288)		325 (347)

5.3.4 Characterizing Tensile Properties

For fully characterization of X100 tensile properties, tests in both the tangential (transverse) and longitudinal direction are required, (the latter being of even greater importance for strain based design of pipelines). The following examples shown in Tables 5.10 and 5.11 of data published by Shell were given in the original paper. The column headed "grade class" identifies the minimum class of steel in API-5L terms commensurate with the achieved tensile results.

Table 5.10
Summary of Pipe Body Transverse Tensile Test Results (averages)

Pipe	0.5% Yield (MPa)	UTS (MPa)	YS/UTS	Elongation (%)	Grade class
Pipe A	678	847	0.80	30.7	X90
Pipe B	661	825	0.80	30.3	X90
Pipe C	663	781	0.85	33.2	X90
Pipe D	651	805	0.81	35.3	X90

Table 5.11
Pipe body longitudinal flattened strip tensile test results (averages)

Pipe	0.5% Yield (MPa)	UTS (MPa)	YS/UTS	Elongation (%)	Grade class
Pipe A	700	849	0.82	32.4	X95
Pipe B	628	809	0.78	34.2	X80
Pipe C	654	753	0.87	33.0	X85
Pipe D	640	790	0.81	36.2	X90

Lessons drawn from the characterization of these early pipes were that all fell short of meeting the full X100 property requirements; a deficiency that has been overcome in later materials. None of the suppliers met the X100 specification for longitudinal strip tensile tests and this has later been recognized as unachievable unless sacrifice is made in terms of other properties, particularly toughness. Also, if the minimum 690 MPa (100 ksi) yield strength were to be achieved in the longitudinal direction, the corresponding implication is that the transverse yield strength could be considerably higher, creating further problems in the selection of weld consumables for over matching.

As steel strength increases, it is important to examine other data from the tensile tests and strain capacity, including ultimate elongation (uniform strain) *Ag* at the ultimate tensile strength. [8] Detailed results are given in the original paper and led to the conclusion that some values of *Ag* were too low and/or that some materials had insufficient strain capacity or that uniform strain was position dependent around the circumference of the pipe.

5.3.5 Characterizing the Seam Weld

The technique of characterizing the seam weld essentially comprised taking all-weld metal tensile tests and cross-weld tests. This is relatively straightforward for the larger SAW longitudinal seam welds made in the mill but in later work, adapting the technique to the more confined narrow-gap girth welds proved less easy for the all-weld metal tests and as both position from which a tensile blank was prepared and the geometric form of the test piece would markedly affect results. Cross-weld testing remained feasible for later girth weld evaluation. Examples taken from the published paper are as shown in Table 5.12

Table 5.12
Results of all-weld metal and cross-weld tensile tests on Early X100 Seam Welds [8]

Pipe	**All-weld metal (round bar)**						**Cross weld (strip)**	
	0.5% Yield (MPa)	UTS (MPa)	YS/TS	Strain at UTS (%)	Elong. (%)	Reduction in Area (%)	UTS (MPa)	Remark
Pipe A	747	842	0.89	3.87	20.3	70	799	Failed in HAZ
Pipe B	714	816	0.88	3.87	19.8	68	768	Failed in HAZ
Pipe C	690	758	0.91	5.86	23.3	69	780	Failed in weld
Pipe D	675	877	0.77	6.42	21.8	63	843	Failed in FL/HAZ

5.3.6 Characterizing Toughness of Parent Pipe and Weld Seams

Shell conducted extensive fracture mechanics testing (Charpy, DWTT and CTOD) on the seam weld and the seam-weld HAZ as part of the JIP, results of which can be found in the conference paper. [8] At that time it became evident that the low fracture toughness of the HAZ would pose problems with conventional engineering critical assessment methods but a literature search found that this was a problem not confined to high strength steels alone. A more advanced fracture mechanics analysis method (constraint based fracture mechanics - CBFM), which reduces the conservatisms of conventional fracture mechanics, was then used to assess the seam weld. This advanced fracture mechanics approach and its comparison to full-scale ring tests was described in other papers. [9, 10]

Charpy temperature transition curves for the parent material, HAZ and weld metal are illustrated the published paper. The lower-bound curve fits were used to illustrate the difference between the upper/lower shelf and transition temperatures regions for the different suppliers. For actual data and the inherent scatter. [8]

For the parent material, pipes A, C and D all had upper shelf Charpy toughness levels in the order of 200 to 250 J and high levels of upper shelf CVN have characterized later X100. At the time Pipe B had an upper shelf Charpy toughness of 125 J but later material from the same supplier is known to have been supplied for later trials. The lower shelf temperatures of -60°C (Pipe A), -80°C for pipes B and C and even -100°C for pipe D were determined.

All four preproduction pipes met the drop weight tear test (DWTT) requirements.

Great variation occurred in the HAZ Charpy transition curves for the different pipes and transition temperatures were higher than for the parent material or weld metal in two cases being as high as the target design temperature of 0°C.

The upper shelf HAZ toughness values of around 60J to 80 J were noted except for pipe C which was above 100 J. The low HAZ Charpy toughness for Pipes B, C and D around the design temperature was a cause for concern.

The weld metal (centerline) Charpy transition curves for pipes A, B and C were similar and nearly coincident. Upper shelf energy values of the order of 130 J to 150 J with the lower shelf starting at approximately -40°C were noted. Pipes A, B and C all had acceptable weld metal Charpy toughness result whereas Pipe D weld gave marginal results. These issues are understood to have been addressed in later production of X100.

Further characterization of zones of each pipe was done by CTOD tests and temperature transition curves for the parent material, HAZ and weld metal are reported in published papers. [8, 9, 10, 11, 12]

5.3.7 Characterisation of Later High Strength Pipes

Results of the work conducted by Shell as part of the JIP characterized the early X100 and set the pattern for further evaluations (e.g. by Hudson) and feedback of the results to the pipe manufacturers undoubtedly assisted in formulation of the next generation prototype and ultimately the production X100 steel pipe.

5.4 Fracture Control Requirements

Toughness requirements for arrest of running fracture in X100 are not covered and probably cannot be predicted by methods such as the EPRG Guidelines or by the Battelle two-curve methods which are effectively limited to X80 (Grade L555). The AISI method (an equation that was statistically fitted to full- scale burst test data is limited to a narrow range of test data against which it was originally calibrated and does not go above X70. This is recognised in Annex G of ISO 3183:2007 and the 44th Edition of API 5L which states the limits for each method. At the present time, the only way of assessing the arrest toughness for the higher strength pipes such as X90, X100 and X120 is by means of a full-scale burst test (which is the fifth optional approach specified in the ISO/API harmonised standard).

A number of full-scale burst tests have been conducted on X100 (L630) line pipe, some by Advantica Technologies Ltd at their Spadeadam site in the UK and others by Centro Svilluppo Materiali (CSM) at their site in Perdas de Fogu, Sardinia. [39, 40, 41] Full data from these tests is not yet in the public domain but is held by the sponsoring consortia or individual sponsoring companies in each case. The size range over which tests have been conducted range is understood to be from 762 mm to 1321 mm (30 in. to 52 in.) with pipe wall thicknesses ranging from around 12 mm up to 20 mm.

Conventionally, a full scale burst test comprises a horizontal string of 7 or 9 test pipes incorporating a centrally positioned “starter” pipe of slightly lower toughness and containing an initiating notch at its 12 o'clock centre position. The test pipes are laid outwards in each direction and with pipes of increasing toughness towards the outer positions. The pipe string is then welded into the test loop via substantial crack arrestors to protect the accumulator pipes in the event that the fracture in the test pipes fails to arrest. The rationale of the test is that hopefully the increasing toughness pipes will arrest the running fracture and provide an indication of the toughness required for arrest. Detonation of an explosive charge at the starter-pipe notch position is used to initiate a running fracture.

An alternative concept to the increasing toughness pattern in the pipe string is to have all pipes of uniform high toughness that effectively turns the full-scale burst test into a "go/no-go" test. This may be expensive if multiple tests are required but probably demonstrates the required toughness level with a higher degree of certainty. It is understood that one sponsor planned to conduct such tests on X100 in 2008.

Although quantitative data has not been published, it is generally accepted that an X100 pipeline of typically 762 mm (30 in.) diameter transmitting dry, lean composition natural gas will require toughness in excess of 200 J Charpy for arrest of running ductile fracture. Although pipe mills are capable of producing X100 pipe with such Charpy toughness, securing guarantees or toughness at this levels for the complete order may present an obstacle. Where a pipeline will be required to transmit richer composition gas, the full-scale burst test may be the only way to assess the toughness levels required and Charpy toughness values close to 300 J may not provide adequate protection and, in any case, such values may not be achievable in the parent pipe or the supplying pipe mill may decline to guarantee such high values, even if achievable. In such cases, crack arrestors will need to be designed into the pipeline.

5.5 Crack Arresters

There are several types of crack arresters that may be used for an X 90 or X100 pipeline including:

- Thick scantling, high toughness pipe which may be of the same strength or possibly a lower strength steel but heat-treated for high toughness. Such pipe might be rolled or forged but a more highly alloyed chemical composition may need to be used and this may adversely affect weldability. Also a higher alloy composition may adversely affect toughness unless a quench and tempered process is used in manufacture.
- Composite wrap pipe. This type of crack arrestor utilises a multi-layer composite material wrap around a pipe of the same type and grade as used for the pipeline construction. This is sometimes referred to as Clock Spring®[3] wrap after fittings made by a similar technique. This has proved to be an effective crack stopper in one burst test but, in extreme conditions, may not prevent a running crack re-initiating in new unreinforced pipe after the crack arrestor.
- Wire-rope crack arrestors. This type of arrestor may not be a practical proposition for deployment at regular intervals along a gas pipeline and, unless properly protected, may be subject to corrosion. However, it has been used successfully to protect accumulator pipes in test loops for full scale burst test assemblies.

[3] Clock Spring® is a registered trademark of NCF Industries, Inc. Corporation of California, Highway 1, Cayucos CA 93430

- Grouted sleeve wraps. The principle of the grouted sleeve is to reinforce the parent pipe with an increased scantling which must be tight fitting to resist internal pressurisation that would otherwise burst the inner pipe. This requires minimum clearance between the pipe and sleeve and a mechanism where by a liquid grout can be injected so that it penetrates the orifice uniformly and evenly, so that when it solidifies it forms an effective load transfer mechanism between the pipe and sleeve. Although of substantial appearance it is uncertain how effective this is as a crack stopper and any non-uniform bonding between grout and pipes may markedly reduce its effectiveness. Also, after stopping a running crack in practice, the grout bond may be damaged or destroyed and the crack arrestor may have to be replaced.
- Metal-metal shrink-fit sleeve. In principle this might be considered as an alternative to the grouted sleeve and, since the sleeve will exert a compressive force on the inner pipe, may be effective. However this may be expensive to manufacture and no details are available.

Although some types of crack arrestor have been developed and tested, not all are proven. This may be a partial technology gap requiring specification and testing to prove fitness for service.

The transition joint between a crack arrestor and a line pipe needs to be specifically designed particularly where the scantling of the crack arrestor is significantly greater than that of the line pipe it is protecting.

The need for crack arrestors is an additional expenditure and in some applications may swing the economics from high strength pipes to lower grade materials.

5.6 Limiting Service Conditions

The limiting service conditions for each pipeline are a combination of the specified operating parameters and environmental conditions and will be unique for every pipeline.

Only a few sections of X100 or X120 pipeline have been installed to date and, those sections currently in service were installed more as a construction feasibility trial than to exploit the high strength properties of the pipe to the full. Therefore very little data on limiting service conditions is available. The following notes suggest individual items needing evaluation and featuring in the design parameters for the pipeline.

- Minimum design temperature. The minimum design temperature is usually based on the minimum monthly mean temperature for the location where the pipeline is to be laid. The arctic regions impose the greatest challenge and, for example, the average temperature for Barrow, Alaska is -12.6ºC the minimum average is for the months of February at -27.7ºC (with an average maximum and minimum for the same month of -24.3ºC and -30.9ºC respectively. Individual spot temperatures may be considerably below the monthly minimum. This imposes the challenge of obtaining sufficient toughness in the X100 or X120 pipe and in weld metals particularly for sections of the pipeline that are not buried. (The design temperature for buried pipelines in arctic regions may be less extreme). Testing of X100 has generally demonstrated high conventional Charpy toughness at -40ºC, providing high resistance to brittle fracture. However, it should be noted that for fracture control purposes, full scale burst tests have indicated that CVN values even above 200 J at 0ºC cannot guarantee freedom from running ductile fracture and that crack arrestors may need to be built in to the pipeline at specified intervals. Some pipe mills may be loathe to accept a mandatory drop weight test (DWT) minimum of 85% shear fracture at a test temperature of -40ºC, although they may be prepared to conduct such tests where results are supplied for information. Where pipelines are built in locations with higher ambient temperatures, minimum design temperature will be less of a constraint.

- Design Factor. Traditionally pipeline design factors of 0.72 were used but within the last decade there has been a progressive move towards 0.8. This requires careful consideration of the tensile properties of the line pipe and, in particular, the stress-strain curve. The modern TCMP produced steels typically have a higher yield to tensile ratio and ISO 3183 / API 5L allow this limit up to 0.95 for X90 (L 625M), 0.97 for X100 (L 690M) and 0.99 for X120 (L 830M). At first sight this may cause some concern when coupled with a planned 0.8 design factor so it is important that the shape of the stress-strain curve is reviewed as some of these steels have a considerable post-yield extension capacity, albeit with little or no rising load. ISO 3183 / API 5L does contain a provision allowing alternative $R_{t\,0.5}/R_m$ limits by agreement. In practice, lower yield to tensile values can be obtained particularly for the longitudinal direction properties.
- Strain Based Design. For strain-based design pipelines, the shape of the tensile stress-strain curve assumes greater importance where pipelines are built in locations with unstable foundations which permit pipe movement and/or unsupported spans. This can typically occur in arctic areas where alternate thaw and freezing may result in frost heave or sinking and in extreme cases where seismic activity may result in sudden and drastic shift of pipeline position. Total strain capacity of the line pipe is important in such instances. The mechanical properties of the longitudinal or helical weld seam of the high strength line pipe must also be evaluated to ensure sufficient strain capacity is available. Although no details of results are published it is known that oil/gas and line pipe manufacturing companies have conducted strain tests of pipes under internal pressure to simulate movement under operational and environmental as well as the yield and tensile values is important.
- Pipeline Inventory. At the present time, the anticipated application for higher strength line pipe such as X90 or X100 is transmission of dry, non-sour natural gas although these steels would also be suitable for transmission of sweet crude oil if required. These steels have not been evaluated for use with sour wet natural gas or sour crude oil inventories. Typical hardness values of girth welds and their associated heat affected zones can exceed 300 HV and, as such may render such joints susceptible to sulfide stress-corrosion cracking.
- Cathodic Protection. The effects of CP (or over protection) on X100 steel have been investigated but results may not be in the public domain. In the event of hydrogen generation as a result of over-potential, an area of possible concern would be the intersection of girth welds and line pipe seam-welds where the higher alloy content of the latter may result in greater local hardening.
- Fracture Control. The anticipated use of X100 line pipe is in construction of long distance, large diameter, high pressure gas transmission pipelines. Fracture control (resistance to brittle fracture and arrest of running fracture) in gas pipelines is required. At present the experimental points and data relating Charpy energy to adequate fracture control in both the EPRG guidelines and Battelle simplified equation and two curve methods are validated only to X80 (L 555) grade line pipe and for dry, lean composition natural gas. Such data is not valid for rich gas compositions nor for pipe grades such as X90, X100 and X120. Several full-scale burst tests have been conducted for individual companies and group sponsors by Advantica, Spadeadam in UK and by CSM, Perdas de

Fogu, Sardinia. Results of those tests remain confidential to the sponsors but indicate that large diameter X100 pipelines, typically 30-36 in (762 - 914 mm diameter), will require a high level of Charpy toughness to guarantee arrest of running fracture. The equation relating the minimum Charpy energy required to arrest running fracture in pipe grades from X70 - X80 (L 485 - L 555) from the EPRG and Battelle simplified method is $K_V = C_3 \times \sigma_h^2 \times \left(\frac{Dt}{2}\right)^{1/3}$ indicating that the required energy is both hoop stress and diameter related. Thus, the required Charpy energy may be attainable in a lower diameter X100 pipeline but may present a considerable challenge for larger diameter pipelines operating at higher pressure which is precisely the market at which X100 is aimed. Typically for X100 lean composition gas pipelines operating at a design factor of 0.8, the equations estimate the following minimum Charpy requirement in the pipe body shown in Table 5.13.

The simple example shown above indicates that while the estimated CVN may be readily achievable for the 508 mm (20 in.) diameter pipe (and it is still a high figure in conventional terms) the value required for 30 in (762 mm) diameter pipe is much more of a challenge and the figure estimated for the 48 in (1220 mm) pipe may not be attainable.

Table 5.13
Estimated Charpy Energy required to Arrest Running Fracture in an X100 pipeline with lean composition gas

Diameter		Wall Thickness		Kv (CVN)
in	mm	in	mm	Joules
20	508	0.75	19.05	146
30	762	0.75	19.05	210
48	1220	1.00	25.4	274

6. Welding of X100 General - Early Trials

6.1 Welding processes suitable for X100.

Early welding development work was carried out in the late 1990's as part of a joint industry project (JIP) funded by Shell, British Gas and BP who investigated the weldability and simulated field welding characteristics of the four pre-production X100 pipes and surveyed candidate welding consumables. [66] Full results of this work have not been widely published and the pre-production parent high strength line pipe did not fully meet all requirements of grade L690 (X100). Subsequent developments by the steelmakers and pipe mills of the next generation X100 had already begun as the work described here was nearing fruition. Although no longer representative of the latest generation of X100, the work described here is of historical significance and paved the way by identifying some welding consumables, providing an early indication of weldability of these high strength steels and guidance to later investigators.

The weldability of the parent pipes was investigated via the Tekken test in an attempt to establish typical preheat levels and a series of weldments were made using the SMAW and GMAW processes for weldability and weldment property assessment.

A theoretical study carried out with CRC-Evans [67] examined the feasibility and economics of field welding using mechanized GMAW, drew on experience of X80 construction and was used to identify candidate filler materials.

Overall, the X100 pipe supplied was deemed weldable by the SMAW and GMAW processes although the tests did not include full qualification testing for specific applications. SMAW electrodes included some cellulosic-coated electrodes which under-match X100 parent metal and, as shown later, are not recommended. The low hydrogen electrodes were variable in performance and showed poor handling characteristics for pipeline applications although they more readily achieved the X100 mechanical properties than the cellulosic electrodes. Despite some cracking and welder induced defects the mechanized GMAW welds, three combinations of GMAW wires were tested and found to be suitable, although all produced weld metals with high hardness values in the weld cap. Further candidate GMAW and flux-cored/ metal cored tubular candidate electrodes for X100 were identified in separate studies, although these were not tested in the initial programme.

6.2 Pipeline Welding in X100

Pipeline construction rates are determined by the time taken to deposit the root pass of a girth weld. Although several welding processes could be used to deposit an acceptable root pass in X100, there are really only three processes which are routinely used, namely:

- Shielded Metal Arc Welding (SMAW).
- Mechanized Gas Metal Arc Welding (GMAW).
- Submerged-Arc Welding (SAW).

Shielded metal arc welding is usually referred to as “stove-piping” in the pipeline construction industry. Stove-piping involves the use of a cellulosic electrode, used in the vertical-down direction, to achieve a high deposition rate.

Mechanized GMAW is also used widely for pipeline welding, and various systems are available. Generally, welding is performed from the outside of the pipe with welding heads (or ‘bugs’) mounted on to a band around the pipe. The bevel is usually of a narrow-gap design to reduce the amount of weld metal required to complete the joint. Accurate bevel preparation is achieved by means of a purpose built pipe-facing machine (PFM). All systems employ an internal line-up clamp (ILUC). Two systems can deposit the root pass from the inside and the welding torches are incorporated into the ILUC. Other systems employ ILUC’s with copper backing shoes, allowing the root pass to be deposited from the outside. Although mechanized GMAW is predominantly a field welding technique, it may prove effective for double jointing of line pipes in the mill or a purpose built double jointing station on the basis that its deposits meet the X100 mechanical criteria more effectively.

Submerged arc welding is often used for making double or multiple joints; that is where two full lengths are joined together prior to being welded into the mainline. Of the conventional pipeline welding techniques this offers perhaps the best productivity and reliability. However, due to the nature of the process, it can only be used in the 1GR position (i.e. downhand) with the pipes being rotated. For X100, the high heat input (particularly if double or multiple wire is used) may result in a wide and soft HAZ as experienced in SAW of longitudinal seam welds made in the pipe mill. Also experience has shown that the SAW wires need to be highly alloyed to meet the high strength requirements in the as welded condition.

The main objective of the welding development work was to extend the use of the conventional welding techniques to include X100 line pipe.

6.3 Consumables—Filler Wires, Electrodes and Fluxes

At the beginning of the initial investigations no suitable consumables were available commercially for welding X100 grade line pipe. This was expected to be the case as consumable welding technology tends to lag behind line pipe technology. Following discussion with consumable manufacturers and by development on their part, some consumables became available as test electrodes and wires, a number of which have been evaluated.

Shielded Metallic Arc Welding (SMAW)

- Böhler Thyssen BVD 110. Low hydrogen vertical-down electrode (AWS A5.5E11018-G)
- Filarc 108 MP Low hydrogen vertical-down electrode (AWS A5.5 E10018-G)
- Nittetsu L80 Low hydrogen electrode (Similar to AWS A5.5 E11016-G)

Flux Cored Arc Welding (FCAW-G)

ESAB Tubrod 15.27 (E110TS-G)

Gas Metal Arc Welding (GMAW)

- Thyssen NiMo80
- Thyssen NiMoCr (ER100S-1)
- Böhler X70 IG
- Sumitomo SMH 80

Typical chemical compositions and mechanical properties, as quoted by the manufacturers, probably on the basis of conventional electrode classification welds (rather than pipeline welding procedure qualification tests) are tabulated below in Table 6.1.

Table 6.1
Chemical Compositions of Welding Consumables for X100

Consumable Name/Type		Chemical composition (wt%)							As-Welded Mechanical Properties		
Name	**Type**	**C**	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**V**	**YS MPa**	**UTS MPa**	**Elong (%)**
Rod	Rod	0.07	0.40	1.50	-	2.00	0.30	-	670	760	15
108 MP	Rod	0.09	0.70	2.00	-	1.60	-	-	600	690	22
Nittetsu L-80	Rod	0.05	0.44	1.35	0.18	2.52	0.54	-	740	830	24
Tubrod 15.27	Cored Wire	0.06	0.50	1.60	-	2.50	-	-	690	730	15
NiMo80	Wire	0.10	0.60	1.25	-	1.25	0.30	-	≥540	≥630	> 21
NiMoCr	Rod	0.08	0.60	1.70	0.20	1.50	0.50	-	≥680	≥740	> 17
X70IG	Wire	0.10	0.60	1.60	0.30	1.00	0.25	0.10	≥690	≥790	> 16
SMH 80	Wire	0.08	0.52	1.31	0.19	2.80	0.47				

6.4 Weldability of Experimental Line Pipe

A major concern about any high strength steel line pipe is its susceptibility to hydrogen induced cracking (hydrogen assisted cold cracking). Since many pipeline welds are made by the manual "stovepipe technique" in a vertical-down direction with cellulosic coated electrodes, the risk of hydrogen induced cracking cannot be ignored. The growing use of processes such as mechanized GMAW, that are generally much lower hydrogen potential, reduces this risk and it is probable that mechanized GMAW will be a major contender for main line welds in large diameter X100 pipelines. This will arise as a result of both economic and technical advantages of the mechanized processes.

The susceptibility of the four sample X100 pipes to hydrogen cracking when welded with cellulosic electrodes was evaluated in early trials by a version of the Tekken test modified to simulate field welding.

After preheating each assembly uniformly a test weld root run was deposited in the PA (1G) position at a specified heat input of 0.8-1.0 kJ/mm and the hot-pass was deposited 5 minutes after completing the root at a heat input of 1.0-.1.2kJ/mm. Electrodes used were 4 mm diameter Böhler Fox Cel 90 (E 9010G) and Böhler Fox Cel Mo (an E 7010-A1 electrode which under-matches the parent X100 Sections were taken from each assembly 72 hours after welding and examined microscopically for cracks. Hardness measurements were also made.

Tests that were not preheated or preheated to only 50°C resulted in cracking of the test weld, irrespective of whether the adjacent material was parent pipe or the higher CE pipe longitudinal weld. Only when a preheat of 65°C was applied did this position improve although cracking of the test weld, adjacent to the longitudinal weld persisted in two pipes even after preheat to 80°C. Selective tests, made with preheats of 110 °C and 140°C, indicated that welds could be made crack-free between the base metals.

6.5 Girth Welding Trials on Experimental Line Pipe

A limited series of girth welds were made on experimental X100 line pipe to determine whether conventional welding processes could be used successfully. Three processes were considered, namely:

- SMAW
- FCAW-G
- Mechanized GMAW

6.5.1 <u>SMAW & FCAW</u>

SMAW welding procedures used for the trials utilized cellulosic electrodes for the root and hot pass, with low hydrogen vertical-down electrodes for the fill and cap passes. Low hydrogen vertical-up welding was not considered viable at the time. The pipe ends were prepared with a 30° bevel, (60° included angle weld preparation), the seam welds were offset by 180° (at 3 and 9 o'clock), and welding was performed in the 5G (PF or PG) position.

SMAW electrodes used were BVD 110, 108 MP, and L80.

Only one FCAW wire was used, namely: ESAB Tubrod 15.27. A 30° bevel was used and welding took place in the 5G position. The wire was used with gas shielding. Typical welding parameters are given in Table 6.2 below:

Table 6.2
Welding Parameters for Early X100 Test Welds

Pass	Polarity	Consumable	Size (mm)	Amps	Volts	Heat Input (kJ/mm)
Root	DCEN	Fox Cel Mo	4.0	135	27	0.6
Hot Pass	DCEP	Fox Cel 90	4.0	150	26	0.8
Fill & Cap	DCEP	BVD 110	4.5	200	21	1.0
Fill & Cap	DCEP	108 MP	4.0	210	20	1.0
Fill & Cap	DCEN	Tubrod	1.2	160	23	1.2

Weld metal properties are summarized in Tables 6.3-6.5. The data [68] suggested that none of the consumables would comfortably meet the strength requirements for X100. However, the consumable evaluation test conditions are not always representative of pipeline welding conditions and this difference is emphasized in the following sections for manual and mechanized welds.

The trial SMAW weld procedure used cellulosic electrodes for the root and hot pass, with low hydrogen vertical-down electrodes for the fill and cap passes. Low hydrogen vertical-up was not considered viable. The pipe ends were prepared with a 30° bevel, the seam welds were offset by 180° (at 3 and 9 o'clock), and welding was performed in the 5G (PF) position.

Table 6.3
All-Weld Metal Tensile Properties (Early X100 Test Welds)

Consumable	All-Weld Tensile Test	
	0.2% Proof Stress (MPa)	Tensile Strength (MPa)
BVD 110	741, 746	812, 812
108 MP	666, 749	764, 818
Tubrod 15.27	596, 659	694, 741

Table 6.4
Charpy Impact Values (Early X100 Test Welds)

Consumable	Charpy Impact Values (Joules), 10x10x2mm @ -10°C, root.		
	Weld	FL	FL+2
BVD 110	83 - 115	69 - 156	178 - 254
108 MP	67 - 93	55 - 85	214 - 273
Tubrod 15.27	104 - 170	53 - 160	244 - 267

Table 6.5
Cap Hardness of Early X100 Test Welds

Consumable	Maximum Cap Hardness (HV10), at 3 and 9 o'clock positions		
	Weld	HAZ	Parent
BVD 110	294	339	285
108 MP	279	333	290
Tubrod 15.27	285	314	294

Table 6.6
Typical CTOD Values of Early X100 Weld Metal

Consumable	Crack Tip Opening Displacement (mm), 2BxB specimens, tested at 0°C.	
	Weld	Fusion Line
BVD 110	$\delta_u = 0.16$	$\delta_u = 0.2 – 0.3$
108 MP	$\delta_u = 0.15$	
Tubrod 15.27	$\delta_m = 0.50$	

The Böhler BVD 110 electrode is a basic, low-hydrogen consumable that can be used in the vertical-down direction. The all-weld yield strength exceeded the manufacturer's stated values and comfortably met the requirements for X100. The Charpy impact toughness, CTOD and hardness values were also generally acceptable.

The Filarc 108 MP electrode produced a weld having an all-weld yield strength of 666 MPa and 749 MPa. Further testing would be required to confirm the all-weld yield strength that could be reliably achieved with this electrode. The Charpy impact toughness, CTOD and hardness values were also acceptable for welds produced from this electrode.

The L80 electrode was found to be unsuitable for vertical-down welding despite being advertised as an extra-low hydrogen, all-positional electrode with high resistance to moisture absorption and depositing weld metal with excellent mechanical properties and X-Ray quality. However, it appears to have been developed for applications such as penstocks, pressure vessels, bridges, machinery and turbine casings rather than pipe lay welding.

The deposit from the ESAB Tubrod 15.27 FCAW wire did not meet the requirement for all-weld yield strength, and the values achieved were lower than those stated on the manufacturer's datasheet. However, the Charpy impact toughness values and CTOD values obtained for the Tubrod 15.27 weld metal were excellent along with acceptable Vickers hardness values.

6.5.2 Mechanized GMAW

The trial GMAW weld procedure used an internal root pass, followed by a hot pass, fill passes, and cap pass made from the outside. Due to the limitations of the equipment available the root pass was made using semi-automatic GMAW, in the 2G (PC) position, and with an external clamp.

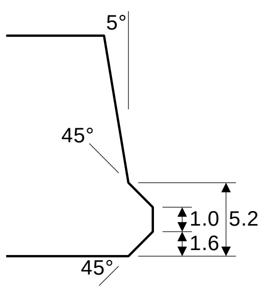
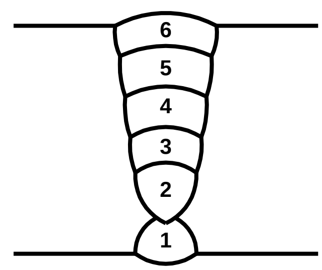
The following wires were evaluated:

- Thyssen NiMo80
- Thyssen Union NiMoCr
- Böhler X70 IG
- Sumitomo SMH 80

An example of welding parameters is shown below in Table 6.7.

Magnetic Particle Inspection (MPI) of the internal root bead revealed transverse cracks in the root pass weld metal that were also detected by X-radiography. The transverse cracking appeared to be associated with regions of excess penetration, excess hi-lo, stop/starts, and in proximity to the seam welds.

Table 6.7
Example of Welding Parameters (Early X100 Weld Trials)

Pipe Size: 762 mm (30 in.) Diameter x 19 mm	No. Welders: 1 (Root), 1 Others
Grade: X100 X100	Preheat: 100ºC min
Position: 2G (Root) , 5G (Hot Pass and Fill)	Interpass: 250ºC
Clamp: External for 100% Root	
Joint Design: 	Pass Sequence: 

Pass	Wire Diameter (mm)	Gas Mixture	WFS (m/min)	Amps	Volts	Travel Speed (cm/min)	Heat Input (kJ/mm)
Root	1.0	80Ar/20CO_2	7.6	200	21	35	0.5
Hot pass	1.0	CO_2	10.2	260	24	50	0.3
Fill-1	1.0	CO_2	10.2	240	25	38	0.8 – 1.1
Fill-2	1.0	CO_2	10.2	240	25	38	0.8 – 1.1
Fill-3	1.0	CO_2	10.2	240	25	38	0.8 – 1.1
Cap	1.0	80Ar/20CO_2	7.6	190	21	33	0.7 – 0.8

Whilst the results were disappointing, they were also inconclusive - due mainly to the unorthodox method of making the root pass. Further welding work was recommended to demonstrate the suitability of mechanized GMAW for welding X100.

The mechanical properties obtained for the mechanized GMAW weld are summarized below in Tables 6.8 – 6.11.

The NiMo80/NiMoCr wire combination gave all-weld tensile values that comfortably exceeded the minimum yield strength specified for X100. The Charpy impact toughness values and CTOD values for the weld metal were reasonable. The weld metal cap hardness value of 309 HV10 was slightly over the specification limit of 275 HV10. The weld metal hardness resulting from mechanized GMAW depends upon several inter-related factors including weld filler wire and parent pipe steel compositions, weld dilution and weld cooling rate. Weld cooling rate depends on arc energy, travel speed, preheat and inter-pass temperatures and the heat sink effect of the pipe being welded. The modern mechanized GMAW-P girth welding systems run at high welding speeds leading to high cooling rates that can be balanced to some extent with preheat. The NiMo80/X70-IG wire combination gave the highest all-weld tensile values.

Table 6.8
Tensile Properties of Early Mechanized GMAW Welds in X100

Consumable	All-Weld Tensile Test	
	0.2% Proof Stress (MPa)	Tensile Strength (MPa)
NiMo80 (root), NiMoCr	772, 728	842, 826
NiMo80 (root), X70 IG	821, 850	921, 931

Table 6.9
Charpy Toughness of Early Mechanized GMAW Welds in X100

Consumable	Charpy Impact Values (Joules) 10x10x2mm @ -10°C, root.		
	Weld	FL	FL+2
NiMoCr	62 - 77	226 - 252	242 – 262
X70 IG	49 - 95	225 - 247	234 – 259

Table 6.10
Peak Hardness Values of Early Mechanized X100 GMAW Welds

Consumable	Maximum Cap Hardness (HV10) at 3 and 9 o'clock positions		
	Weld	HAZ	Parent
NiMo80 (root) NiMoCr	309	317	297
NiMo80 (root) X70 IG	360	333	294

Table 6.11
Weld CTOD Values – Early GMAW Welds in X100

Consumable	Crack Tip Opening Displacement (mm), 2BxB specimens, tested at 0°C.	
	Weld	Fusion Line
NiMoCr	$\delta_m = 0.14$	-
X70 IG	$\delta_m = 0.10$	-

6.6 Assessment of Cold Cracking Susceptibility

Hydrogen-assisted cracking (HAC) leads to defects which have the most serious consequences, but which are the most difficult to detect by NDT. There are a number of strategies which can be employed to avoid HAC, namely: limiting hydrogen concentration during welding, avoiding stress concentrations, controlling the microstructure, and controlling the cooling rate of the weld. The success of these strategies in controlling HAC is evidenced by the fact that it is common practice in pipeline construction for the NDT crew to follow closely behind the welding crew with the modern technique of automatic ultrasonic testing.

Modern high strength pipeline steels have exceptionally good weldability and so cracking in the heat affected zone (HAZ) is no longer the predominant form of HAC. With X80 and X100 steel grades the most likely place for HAC to occur is in the weld metal. This is a serious problem because the HAC avoidance strategies mentioned above are not wholly effective for the weld metal behaviour. Weld metal cracking was observed during trial welding of early X100 line pipe but the scope of work did not include for a detailed investigation of the problem.

To assist in the determination of the preheat and inter-pass temperatures for field welding, the cracking susceptibility of four pipes and their seam welds was assessed by modified Tekken testing, modified to simulate manual SMAW field welding. A standard API V-preparation with an included angle of 60 degrees was adopted and a root pass followed by a hot pass using typical field welding parameters were deposited. The deposition of the two passes using cellulosic consumables simulated the moment of clamp removal during field welding. The Tekken test was performed using consumables of two strength levels on test sections sampling the pipe body and the longitudinal seam weld.

Where cracking occurred, it was in the weld metal, and a higher susceptibility of weld metal cracking was noted when in contact with longitudinal weld metal. This was as expected because of richer composition of the longitudinal weld. Cracking was confined to the deposited cellulosic weld metal of the root and the hot pass.

In parent metals of leaner composition the minimum preheat to avoid cracking is generally lower; however use of lower strength electrodes does not lead to a lower preheat temperature. The base metals of four pipes tested showed a lower susceptibility to cold cracking than the longitudinal weld metals.

Results of the Tekken testing indicated that a preheat of at least 100°C is needed if field welding procedures use cellulosic consumables for the root and hot pass and basic consumables for the fillers and the cap. [66] However, later experience indicated that it is inadvisable to use cellulosic-coated SMAW electrodes for root runs in X100. [69]

Average hardness values measured in the Tekken test weld deposit and HAZ in the base metal as well as test weld and HAZ deposited between longitudinal seam welds are summarized in Table 6.12.

Table 6.12
Average Hardness in Early X100 Test Welds and HAZ

Location	**Steel 1**		**Steel 2**		**Steel 3**		**Steel 4**	
	Base Metal	Long'l Weld	Base Metal	Long'l Weld	Base Metal	Long'l Weld	Base Metal	Long'l Weld
Weld	252	252	245	251	255	249	257	269
HAZ	272	353	271	286	327	264	302	346

6.7 Processes and Procedures For Field Welding X100 Line Pipe

As a chief reason for specifying X100 for pipelines is reduction of cost, the same incentive will apply to cost reductions in the field welding of the pipeline during construction. Some economic advantage will accrue from the thinner wall and/or smaller diameter of X100 pipe in comparison with lower grades leading to lower volumes of weld metal being required per weld.

The SMAW welding process may still find very limited application, probably for short runs, small diameter pipes, branches, off-takes and fittings and possibly for root and hot pass runs for tie-ins but it is unlikely to be a favoured process for long distance main line welding. However, traditional stovepipe techniques using cellulosic coated electrodes is inadvisable.

Tie-in welds require a considerable minimum preheat and close preheat control to ensure freedom from hydrogen induced cracking. It may be necessary to resort to vertical-up welding with hydrogen-controlled electrodes. The SMAW process when applied to pipeline welding usually employs the standard API bevel or a variant of it and, although this is economical at low wall thicknesses, the volume of weld metal required to fill the gap increases significantly with wall thickness.

In the welding of several X70 and the few X80 pipelines, mechanized GMAW has been successful and points to its suitability as a promising candidate for X100. It is also considered that economies can result from high productivity achieved by using of multiple welding bugs. The mechanized GMAW process utilizes a narrow, steep angle welding preparation that reduces the volume of weld metal required to fill the weld preparation

The early trials and studies indicated that the required tensile properties may be more readily achieved with the commercially available GMAW consumables than with SMAW and later trials identified a limited number of solid wires, and flux-cored (FCAW-G) or metal cored (GMAW-C) wires that were potentially suitable for X100 and which can be run on the proprietary equipment.

Finally, technical advances in mechanized GMAW in the late 1990's included a twin-torch variant that further improves productivity and which has been used successfully on an X70 pipeline. Current field pipe-lay practice also links mechanized GMAW with automated ultrasonic testing of pipeline girth welds to provide a rapid results and feedback to the front end as well as a permanent record.

Another potential process for field pipe-lay and particularly for tie-in welding is that of semi-automatic FCAW-G. This would normally employ a standard API bevel or similar, rather than the narrow gap compound bevel of the automated variant but, as the duty cycle would be lower, the economic advantages are likely to be less and repair rates could be potentially higher. Heat input, which is likely to be an important parameter in welding X100, would be less easily controlled. However, the process may be suitable for use in areas of hilly terrain where the fully mechanized GMAW systems may not be operable.

The early trial programmes did not address the welding of double or triple jointing of X100 pipes, yet there are often economic advantages of doing so. Conventionally, the double jointing process would be based on submerged arc welding (SAW) although, for relatively thin wall pipes, an off-line mechanized GMAW double jointing system might be considered.

For SAW double jointing of X100 a survey may be required to identify suitable welding wires and fluxes followed by proving/qualification tests to ensure that the required combination of tensile and toughness properties can be achieved, particularly in respect of heat affected zone softening.

6.8 Identifying Consumable and Welding Processes For X100

The intended primary application of X100 is large diameter onshore gas transmission pipelines for which the favoured process for field girth welding is mechanized GMAW. Early in the development process, one major contractor (CRC-Evans) made a study of consumables for welding X100. In a survey of some 26 welding consumable manufacturers, 11 replies were received and details of the GMAW and FCAW consumables offered were as shown in Table 6.13. The consumables listed include solid wire (S), metal cored wire (MC) and flux cored wire (FC). Further evaluation of individual wires was necessary for later development and qualification test welds on X100. These details identified a limited number of potentially suitable consumables from several suppliers.

Table 6.13
Welding Consumables Potentially Suitable for X100

Manufacturer	Electrode Designation	Type	Yield Strength MPa	Tensile Strength MPa	Elong %	CVN
American Welding Alloys	100S-1 (HX80)	S	No Info	716	18%	60 ft lbs @ - 60ºF
Cigweld	TC 110 TXP	FC	720	800	21%	No Info
Cor-Met	F15FC 800ºF preheat/ip-temp + PWHT	FC	757	792	20%	No Info
Cor-Met	F25FC 800ºF preheat/ip-temp + PWHT	FC	806	909	17%	No Info
Lincoln	LA–100	S	710	772	23%	81-136J @-51ºC
Lincoln	MC–100	MC	689	813	19%	107J @-51ºC
Metrode	Tuf-Met 2NiMo	FC	732	785	24%	90J @-50ºC
Metrode	ER 110 SG	S	660	730	21%	50J @-20ºC
Oerlikon	Carbofil NiMo3	FC	640	710	18%	>80J @-20ºC
Oerlikon	Carbofil NiMoCr	FC	690	790	16%	>50J @-20ºC
Thyssen	NiMoCr	S	740	810	18%	>55J @-40ºC
Thyssen	X85 Union	S	830	900	22%	60J @ -40ºC
Thyssen	NiMo80	S	540	630	22%	60J @-40ºC
ESAB	Tubrod 14.03	FC	855	914	15%	80J @ -40ºC

The following selection from the Thyssen range of wires shown in Table 6.14 was considered potentially suitable for X100 based on the need to develop a matching or over-matching strength weld deposit.

Table 6.14
Thyssen Wires Selected for X100 Welding Trials

	Matching Strength Weld Deposit	Overmatching Strength Weld Deposit
Root Pass	K-Nova (1)	K Nova (1)
Hot Pass	NiMo80 (2)	K Nova
Fill Pass	NiMo80	NiCrMo
Cap Pass	NiMo80	NiCrMo

The use of K-Nova was recommended for the root run to minimise the risk of root pass cracking. Although theoretically, the NiMo80 appeared slightly low on yield strength, it gains added strength when deposited in a narrow gap at the typical heat inputs associated with automatic GMAW. The use of mixed gases or GMAW-P was considered to increase the actual yield strength.

7. Welding of X100 - Detailed Trials and Procedure Development

7.1 Introduction

Around 2000 - 2001, major technical development work on welding X100 steel line pipe began and, as part of a substantial technical evaluation of X100 line pipe which had to be undertaken to evaluate the steel for all aspects of pipeline design, construction and operation, work between 2000 and 2004 centered on the development of specific welding technology for X100 and the development of field usable welding procedures.

At this time, several line pipe manufacturers produced their second-generation X100 steels as full size, pre-production pipes, which generally met the specified technical requirements, and supplied these to oil/gas companies for detailed evaluation.

Among several major tasks to prove the suitability of these materials for service and also to enrol other elements of the industry, including some pipeline welding companies, was development of field welding procedures. At the time, pipeline-welding companies were unable to dedicate the time and resources to a systematic and lengthy development programme on X100 while simultaneously operating their normal pipeline welding business. So, BP and TCPL sponsored development work to The Welding Engineering Research Centre (WERC) of Cranfield University, UK. In turn, WERC collaborated with Serimer-Dasa (France) and with CRC-Evans Automatic Welding Inc., (USA) who provided special equipment and technical liaison.

Cranfield worked closely with the manufacturers and suppliers of welding equipment and consumables and the tripartite collaboration with BP and TCPL extended the reach of the technical development.

The initial challenge was to achieve a minimum weld metal target yield strength of 810 MPa in order to overmatch the yield strength of the parent pipe. It was found that, although the strength level could be readily achieved, the task of simultaneously attaining high elongation, Charpy toughness and CTOD together with acceptable hardness proved much harder to achieve and many iterative experimental welds were made to fine tune the technology to attain the required combination of mechanical properties in the X100 welds. The Cranfield WERC team and Serimer-Dasa succeeded in achieving this end and in qualifying procedures that are representative of field pipeline mainline welding practices.

It must be emphasised, however, that at the X100 strength level, the welding procedures are highly individual and cannot be arbitrarily transferred from one contractor to another. Even changes of equipment or welding process variables by the same contractor are likely to result in some deviation from the desired weld properties. Selection of welding consumable or alloy variant is welding process-type related to a far greater extent than for lower grade line pipe if the desired properties are to be achieved. In short, the welding of X100 is more of a precision business than for many of the lower grades of line pipe and control of the welding process must reflect this fact.

The detail of the Cranfield work in the report [70] proved that the mainline welding of X100 is feasible, subject to application of the requisite control. Procedures were also developed which indicated that repairs can be made satisfactorily. An attempt to develop a tie-in procedure using the FCAW-G process was only partly successful as, although a sound weld was produced and the weld metal strength overmatched the specified minimum yield strength of the parent pipe, the degree of overmatch did not meet the target value of 810 MPa. Improving tie-in welding is identified as a minor technology gap.

7.2 Processes and Procedures

The Cranfield X100 collaborative girth welding developments utilized several wall thickness variants of X100 pre-production pipe sections from more than one pipe manufacturer. The programme of work included single, dual and tandem torch narrow gap mechanized welds that simulated pipe-lay main line welding, alongside manual/ semi automatic repair and tie-in procedures. This was supported by a previous literature search and initial investigation of potential candidate welding consumables for X100 strength line pipe. This was reported in PRCI report number PR-171-9906, although transference of results from the 60° bevel predominantly used in this work, to the narrow gap situation is technically limited due to the joint design and heat input utilized.

GMAW-P conventional short-circuit gas metal arc (GMAW-S), SMAW and FCAW-G were investigated as appropriate to each application. Proposed mechanical property requirements of the weld metal relevant to X100 pipe were established, from which a variety of consumable electrodes were used initially to determine potential weld metal chemical composition levels. This was followed by full weld procedure testing of selective chemistries with conformance to the requirements of existing European and American transmission pipeline welding standards.

7.3 Materials

7.3.1 <u>Line Pipe</u>

Table 7.1 identifies the X100 pipe test materials received from various suppliers via an alphanumeric code to maintain pipe manufacturer confidentiality. [71] The programme used pipe lengths of typically 3 meters, each pipe being individually identified. The three wall-thickness (w.t.) variants of test pipes were 14.9, 16.3 and 19.05 mm. Pipe outside diameters were 762 mm (30 in.) and 914 mm (36 in.).

The X100 pipes were produced from thermo-mechanically controlled processed (TMCP) and accelerated cooled (AC) plate and formed into pipe via the UOE process. Detailed conditions of manufacture are not available and are regarded as proprietary information.

SAWL seams comprised a single pass internal weld and similar external weld deposited by multi-head SAW machines. Chemical compositions of the X100 test pipe base metals are summarized in Table 7.2 which indicates the differing approaches to alloy design of the steel adopted by different manufacturers. [70, 71]

Table 7.1
X100 Pipe Materials Used for Welding Procedures Development [70]

Pipe Supplier	Nominal Wall Thickness, mm	Nominal Outside Diameter, mm (in)	No. of Pipes
A	19.05	762 (30)	12
A	19.05	Plate 1 m x 2 m	6
B	14.9	914 (36)	12
B	19.05	914 (36)	8
C	16.3	914 (36)	8
C	16.3	Plate 1 m x 2 m	1

Table 7.2
Summary of Chemical Compositions of X100 Test Pipe Base Materials [70, 71]

Pipe	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Nb	V	Ti	Pcm	CE
A	0.027	2.00	0.006	<0.005	0.2	0.43	0.48	0.43	0.46	0.05	0.07	0.015	0.22	0.61
B 15	0.066	1.91	0.008	<0.005	0.10	0.02	0.54	0.27	0.27	0.03	0.006	0.013	0.21	0.50
B 19	0.06	1.89	0.008	<0.005	0.18	0.02	0.50	0.26	0.30	0.06	0.005	0.018	0.20	0.49
C	0.055	1.91	0.010	<0.005	0.37	0.03	0.24	0.28	0.01	0.05	0.005	0.02	0.19	0.45

Note: Boron content of the above < 5 ppm. Al content range 0.006 – 0.04%
Note: Pcm = C + Mn/20 + Mo/15 + Ni/60 + Cr/20 + V/10 + Cu/20 + Si/30 + 5B
CE_{IIW} = C + Mn/6 + (Cr + Mo + V) + +)/5 + (Cu + Ni)/ 15

Table 7.3 provides a summary of seam weld metal compositions and clearly demonstrates that an over- alloying approach is necessary to achieve matching of overmatching mechanical properties in the seam weld of the X100 pipe. In some cases, a different combination of SAW welding wires may be selected for the ID and OD welds which was clearly shown as the strategy of supplier B. In three out of the four examples given, the alloy composition of the seam welds is significantly richer than that of the X100 base and must be assessed by careful analysis of both Pcm and CE_{IIW} values. In particular, the individual cocktail of alloy elements does not affect Pcm and CE_{IIW} equally or systematically and a high Pcm does not automatically imply a high CE_{IIW} or vice versa. Potent elements such as boron exert a strong influence on the Pcm value but are ignored by the CE_{IIW} equation (which may not technically be applicable anyway, but is regularly used by welding engineers as an approximate yardstick of weldability). In his thesis, Hudson also reported an alternative factor of CET (BS EN 1011-2) [72] that may be more widely used in Europe than elsewhere in the world. Superficial analysis of Hudson's data has indicated a marginally better correlation between CET (BS EN 1011-2) and CE_{IIW} than between Pcm and CEIIW. (n.b., CET = C + (Mn + Mo) /10 + (Cr + Cu)/ 20 + Ni/40)

As part of the Cranfield X100 development work a through study was made of the test pipe mechanical properties and comparisons were made of the values quoted by the suppliers and values obtained by testing the pipe using round bar test pieces different diameters of and strip type tensile test pieces. A summary of typical results mainly from the Cranfield tests are quoted in Table 7.4 of this report but a more comprehensive picture can be obtained from review of Hudson's thesis 56] where full results are given.

Table 7.3
Summary of Chemical Compositions of X100 Test Seam Welds [70]

Pipe	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Nb	V	Ti	Pcm	CE
A (ID)	0.037	1.64	0.006	<0.005	0.22	0.56	1.10	0.58	0.33	0.03	0.05	0.010	0.33	0.64
A (OD)	0.046	1.62	0.007	<0.005	0.20	0.50	1.09	0.51	0.31	0.03	0.04	0.010	0.33	0.62
B15 (ID)	0.068	1.88	0.009	<0.005	0.13	0.46	0.39	1.04	0.24	0.02	0.007	0.013	0.28	0.73
B15 (OD)	0.063	1.87	0.008	<0.005	0.16	0.34	1.75	0.60	0.26	0.019	0.007	0.016	0.27	0.70
B19 (ID)	0.06	1.99	0.008	<0.005	0.21	0.36	1.00	0.78	0.26	0.04	0.007	0.02	0.27	0.70
B19 (OD)	0.053	1.91	0.007	<0.005	0.20	0.33	2.03	0.63	0.26	0.03	0.007	0.018	0.26	0.72
C (ID)	0.049	1.69	0.012	<0.005	0.38	0.04	0.17	0.34	0.01	0.03	0.06	0.03	0.19	0.42
C (OD)	0.05	1.64	0.012	<0.005	0.38	0.04	0.16	0.35	0.01	0.03	0.06	0.03	0.19	0.41

Note: Some weld deposits contained Boron; others did not.

Table 7.4
Tensile Properties of X100 Line Pipe used for Welding Development [70]

Pipe	Test Piece and Orientation	Yield 0.2% PS MPa	Yield 0.5% Total Extension	Tensile MPa	Elongation %	R of A	Y/T Ratio
A	Round/ Trans	797		819	15.3	79.6	0.95
A	Strip/Trans	741	732	807	32.3		0.92
A	Round/Long'l	751		787	15.0	76.5	0.95
A	Strip/Long'l	752	733	806	32.9		0.93
A	ID Seam AWT			838			
A	OD Seam AWT			761			
A	Strip Trans Weld Seam			822			
B15	Round/ Trans	829	854	909	15.5	73.6	0.91
B15	Strip Trans	692	*664?*	865	28		0.80
B15	Round/ Long'l	658	745	862	16.5		0.76
B15	Strip Long'l	671	685	821	27		0.82
B19	Round/ Trans	671		838	19.5	72.4	0.95
B19	Strip Trans	759	758	856	32.7		0.89
B19	Round/ Long'l	701		847	20.8	71.1	0.83
B19	Strip Long'l	733	723	837	34.4		0.88
B19	ID Seam AWT	829*		891*			
B19	OD Seam AWT	824*		894*			
B19	Strip Trans Weld Seam			838*			
C	Round/ Trans	772		851	20.8	78.5	0.91
C	Strip Trans	705	481	858	30.9		0.82
C	Round/ Long'l	628		824	21.1	73.6	0.76

Note: * Suppliers test results.
Note: AWT is all-weld tensile

The comprehensive test results showed frequent discrepancy between mechanical property values quoted by suppliers and those obtained by Cranfield. There was also significant variation between the identical properties measured with round bar and with strip test pieces although this phenomenon frequently occurs with other grades of pipe. Some variation also occurred when round bar test pieces of different cross sectional area (diameter) were tested; some being more representative of the pipe wall thickness than others. Although some of these observations might be typical of other grades of pipe, the greater difficulty of selecting overmatching girth weld metal for the higher strength X100 underlines the need for precise specification of the tensile testing method and specimen geometry and size and standardizing these elements between designer, purchaser and manufacture.

The usual phenomenon of transverse tensile strength being higher than that in the longitudinal direction is generally demonstrated but in the samples tested either some anomalies were present or variability of properties occurred. Some variation of mechanical properties from test pieces sampled at different positions around the pipe circumference also occurred but this is typical of most grades of line pipe. Hardness and microstructure comparisons of weld and HAZ were made using transverse macro-sections etched in 2% Nital.

Table 7.5
GMAW Wires used in X100 Welding Procedure Development [70]

Manufacturer	GMAW Wire Name	Diameter	Classification
Thyssen/CRC	K-Nova/ TS-6 (a)	0.9 mm	ER70S-6
Lincoln	Supra Mig®[4] (b)	1.0 mm	AWS 5.18 ER70S-6
Thyssen	Union NiMo80 (~Union MoNi) (a)	1.0 mm	AWS 5.28 ER90S-G
Thyssen	Union MoNi (b	1.0 mm	AWS 5.28 ER90S-G
Oerlikon	Carbofil HT (a1)	1.0 mm	AWS 5.28 ER100S-G
Oerlikon	Carbofil HT (a2)	1.0 mm	AWS 5.28 ER100S-G
Oerlikon	Carbofil NiMo-1 (a)	1.0 mm	AWS 5.28 ER100S-G
Thyssen	Union NiMoCr (a)	1.0 mm	AWS 5.28 ER100S-1
Thyssen	Union NiMoCr (b)	1.0 mm	AWS 5.28 ER100S-1
ESAB	OK 13.13 (b)	1.0 mm	AWS 5.28 ER100S-G
Elga	Elgamatic 135 (b)	1.0 mm	AWS 5.28 ER100S-G
ESAB	OK 13.29 (b)	1.0 mm	AWS 5.28 ER110S-G
Bohler	X70-IG (a)	1.0 mm	AWS 5.28 ER110S-G
Bohler	X70-IG (b	1.0 mm	AWS 5.28 ER110S-G
Thyssen	Union X85 (b)	1.0 mm	AWS 5.28 ER110S-G
ESAB	Spoolarc®[5] 120 (a1)	0.9 mm	AWS 5.28 ER120S-1
ESAB	Spoolarc® 120 (a2)	0.9 mm	AWS 5.28 ER120S-1
Oerlikon	Carbofil 120 (a	1.0 mm	AWS 5.28 ER120S-G

Note: a) = Cranfield electrode b) = Serimer electode

[4] Supra Mig® is a registered trademark of Lincoln Global Inc., 1200 Monterey Pass Road, Monterey Park CA 91754.
[5] Spoolarc® is a registered trademark of Alloy Rods Global, Inc., 1105 North Market Street Suite 1300, Wilmington DE 19899

7.3.2 Welding Consumables

Numerous consumables were evaluated during the experimental program for mechanized narrow gap welding. The solid wires were of nominally 1.0 mm diameter (except for the ESAB Spoolarc 120 which was 0.9 mm diameter). A summary of the wire type and classification is shown in Table 7.5.

It should be noted that the strength levels obtained in narrow gap welds made with low welding heat input, are significantly different compared with a typical manufacturer's classification test in a wider joint at higher heat inputs.

The consumables used for the tie-in and repair welds are summarized in Tables 7.6 and 7.7 and include two high strength rutile flux-cored wires and low hydrogen basic SMAW electrodes. The SMAW electrodes were typically of 2.5 or 3.2 mm diameter. Some weld metal diffusible hydrogen contents were measured according to BS EN ISO 3690:2001 [7273] for a solid wire and cored wire to show typical levels encountered; results are shown in [70]. Further weld metal hydrogen levels for numerous welding consumables suitable for X100 narrow gap welding can be found in [74].

Table 7.6
SMAW Electrodes used in X100 Welding Repair and Tie-In Procedure Development

Manufacturer	SMAW Electrode Name	Diameter	Classification
Filarc	Filarc 118	2.5 mm	AWS 5.5 E11018-M
Filarc	Filarc 118	3.2 mm	AWS 5.5 E11018-M
Filarc	Filarc 118	3.2 mm	AWS 5.5 E11018-M
Oerlikon	Tenacito 80	2.5 mm	AWS 5.5 E11018-G
Oerlikon	Tenacito 80	3.2 mm	AWS 5.5 E11018-G

Table 7.7
FCAW Electrodes used in X100 Welding Repair & Tie-In welding Procedure Development

Manufacturer	FCAW/MCAW Wire Name	Diameter	Classification
ESAB	Tubrod 15.09	1.2 mm	AWS 5.29 E111T1-GH4
Oerlikon	Citoflux 110	1.2 mm	AWS 5.29 E101T1-GH4
Oerlikon	Fluxofil M10S	1.2 mm	AWS 5.18 E70C-6C, E70C-6M

Tables 7.8 and 7.9 correlate each proprietary wire with its generic alloy type and identifies the configuration in which it was tested, i.e. single wire, dual torch or tandem wire, the transfer mode, i.e. dip (short-circuiting) or pulsed and typical heat input ranges. More extensive detail can be obtained from Hudson's thesis.

It should be noted that some of the welding consumables were used in multiple welding trials, not all of which produced satisfactory or optimum results. It must also be emphasized that a given welding consumable could produce acceptable results with one process variant but not with another and, if welding or other process parameters were varied even within a single process or procedure, the resultant properties would differ.

Table 7.8 Summary of GMAW Wires, Transfer Mode and Heat-Input for Mechanized Single and Dual Torch Welding Procedure Development

Consumable	Wire Alloy Type	Configuration	Transfer mode	Heat Input kJ/mm* (Typical)
Serimer GMAW-S / GMAW-P Single and Dual Torch Welds				
Union NiMoCr	1.5Ni 0.5Mo 0.2Cr	Single & Dual	Dip & Pulsed	0.52 +/- 0.3
Union MoNi	1.0Ni 0.4Mo	Single & Dual	Dip & Pulsed	0.52 +/- 0.3
ESAB 13-13	0.5Ni 0.25Mo 0.5Cr	Dual	Dip	0.52 +/- 0.3
ESAB 13-29	1.5Ni 0.25Mo 0.25Cr	Dual	Dip	0.52 +/- 0.3
Bohler X70 IG	1.3Ni 0.25 Mo 0.25Cr	Single & Dual	Dip	0.52 +/- 0.3
Carbofil HT	0.5Ni 0.5Mo 0.5Cr	Dual	Dip	0.25 - 0.50
Elgamatic 135	1.3Mo 0.3Mo 0.3Cr	Dual	Dip	0.25 - 0.50
RNS/T Raedelli		Dual	Dip	0.25 - 0.50
Union X 85	1.8Ni 0.5Mo 0.3Cr	Dual	Dip	0.25 - 0.50
Cranfield GMAW -P Welds				
Spoolarc 120	2.5Ni 0.5Mo 0.4Cr	Single & Tandem	Pulsed	0.3/0.4 – 0.7
Union NiMoCr	1.5Ni 0.5Mo 0.2Cr	Tandem	Pulsed	0.3 – 0.6
Bohler X70 IG	1.3Ni 0.25 Mo 0.25Cr	Tandem	Pulsed	0.3-0.6
Carbofil HT	0.5Ni 0.5Mo 0.5Cr	Single	Pulsed	0.4- 0.5 / 0.5- 07
Carbofil NiMo-1	1.0Ni 0.3Mo	Tandem	Pulsed	0.3-0.5 / 0.4-0.6
Carbofil 120	1.85Ni 0.55Mo 0.2Cr	Tandem	Pulsed	0.3-0.6

* Heat input figures have been summarized and rounded. Consult Hudson's thesis for further details

Table 7.9
Summary of Welding Consumables investigated for Repair and Tie-in Welding of X100

Consumable	Process	Wire Alloy Type	Weld Type	Transfer mode	Gas Shield	Heat Input kJ/mm* (Typical)
X100 Tie-in and Repair Welds (Cranfield)						
Filarc 118	SMAW	2.0 Ni 4 Mo	Single pass Backweld	Globular	N/A	0.76-0/.83
Carbofil HT	GMAW	0.5 Ni 0.5 Mo 0.5 Cr	Single pass Backweld	Dip	78Ar/20CO_2/2O_2	0.55-0.58
ESAB OK 15.09	FCAW	2.7 Ni 3Mo	Single pass Cap Repair	Spray	78Ar/20CO_2/2O_2	1.56-1.72
Filarc 118 ESAB OK 15.09	SMAW/ FCAW	2.0 Ni 4 Mo 2.7 Ni 3Mo	Full penetration Repair	Globular Spray	N/A 78Ar/20CO_2/2O_2	1.32-2.16 1.11-1.89
Filarc 118 ESAB OK 15.09	SMAW	2.0 Ni 4 Mo 2.7 Ni 3Mo	Tie-in	Globular Spray	N/A 78Ar/20CO_2/2O_2	1.03-1.92 0.82-1.82
Tenacito 80 Citoflux 110	SMAW	2.2 Ni 0.5 Mo 0.4 Cr 2Ni	Tie-in	Globular Spray	N/A 80Ar/20 CO_2	1.52- 2.10 0.9-1.44
Fluxofil M10 Citoflux 110	FCAW	0.06 C 1.6 Mn 0.5 Si 2 Ni	Tie-In	Spray Spray	78Ar/20CO_2/O_2	1.0 1.0 – 1.35
Fluxofil M10 OK 15.09	FCAW	0.06 C 1.6 Mn 0.5 Si 2.7 Ni 3Mo	Tie-In	Spray Spray	78Ar/20CO_2/O_2	0.3-0.5 1.1-1.14

* Heat input figures have been summarized and rounded. Consult Hudson's thesis for further details

7.3.3 Shielding Gases

Procedures at Cranfield WERC utilized a 82.5% Ar/12.5% CO_2/5% He gas mixture for the mechanized GMAW welds based on thorough previous work that indicated this gas resulted in more stable metal transfer and better mechanical properties [75].
A standard BOC gas, Argoshield Heavy (78% Ar/20% CO_2/2% O_2), identified in earlier Cranfield research [76] was used for the GMAW/FCAW repairs and tie-in procedures, alongside mechanized internal root run GMAW-S.

Three gases were used in producing the mechanized welds at Serimer-Dasa:

- A gas mix of 50% Ar/50% CO_2 for GMAW-S welds
- A gas mix of 80% Ar/20% CO_2 for GMAW-S welds
- A gas mix of 90% Ar/10% CO_2 for GMAW-P welds

Welding Power Sources

Several types of welding equipment were used throughout the X100 welding development programme; selection being based on particular welding applications. The results of many trials indicated that equipment such as welding power sources need to be considered as individual essential variables for X100, even for the same form of welding as minor variations result in the need for some adjustment of parameters when substituting one power source for another. In many cases this might merely involve a standard re-qualification of a welding procedure which might be required anyway if other changes had occurred outside essential variable limits. The following paragraphs describe the equipment used by Cranfield, CRC-Evans, Serimer-Dasa and RMS whose welding trials form the basis of the later X100 field welding.

Single wire narrow-gap welding.

Single wire narrow gap welding trials utilized a Lincoln Power Wave® 455/STT®[6] (designed to give 400A at 100% duty cycle of 10 minutes) in conjunction with their Wave Designer Pro on-line control software. Although the machine has the capability of Lincoln's STT® (surface tension transfer) welding mode, this particular transfer mode was not used in the final waveform developed for the X100 welds. The power source is an inverter type with external wire feed drives on top of the unit. Short-circuiting, spray, pulsed or STT® waveforms for GMAW can be accessed through the software and manipulated via the relevant screens. Previous research on X100 [76, 77] showed a marked improvement in mechanical properties using pulsed metal transfer so this was the only transfer mode examined for the single wire narrow gap application. Although the power source has the capability to water-cool the welding torch, the facility was not used as an air-cooled torch was attached to the welding bug in common with the torch type generally employed in narrow gap pipeline welding.

Dual-torch welding.

Dual-torch welding procedure trials on X100 were conducted by Serimer-Dasa using a Kempii 3500 MIG power source operated in short-circuiting transfer mode. The GMAW-P welds were produced using a Miller Invision™[7] 456P power source with their 564M controller.

Tandem wire welding.

Tandem wire welding development with the objective of enhancing welding productivity on X100 began at Cranfield WERC using Fronius Time-Twin TransPuls Synergic 450 power

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[6] Power Wave® is a registered trademarks of Lincoln Global Inc., 1200 Monterey Pass Road, Monterey Park CA 91754.
[7] Invision™ is a trademark of Miller Electric, A Division of Illinois Tool Works, Appleton WI

sources [78, 79, 80, 81] coupled with a tandem torch designed by WERC. The 100% duty cycle of this machine is 450A for 10 minutes and the main feature of this power source is the ability to specify numerous points on a given welding waveform, generating a synergic curve as well as synchronizing the two power supplies. Synergic control of a power source allows multiple welding settings (usually based on deposition levels) with stable metal transfer throughout the operating range. These power sources offer the possibility to change the phasing between them, but the initial Cranfield work focused on always producing the second wire pulse at the end of the first (effectively 180° out of phase). Pulsing the waveform alternately was deemed essential to avoid the electric/magnetic interactions of two closely spaced arcs, thereby promoting a stable metal transfer. In theory, one drop per pulse was thought to provide the most stable and efficient transfer for positional solid wire GMAW-P. Considerable effort was expended in developing suitable waveforms for narrow gap GMAW-P of X100 with wire of a given diameter [78, 79].

During the course of the tandem welding of X100, new versions of the Fronius power source (TransPuls Synergic 4000), were introduced Figure 7.1 and were used for the remaining procedure trials. These machines offer a 100% duty cycle of 320A for 10 minutes. Although digital in make up, these power sources are less flexible than the original, in that only minor variation from a pre-programmed arc characteristic is possible. The original WERC developed synergic curves for tandem welding of X100 were slightly modified before being uploaded into the machines' welding data bank at the factory. The welding characteristics of the resultant synergic curves were however noticeably 'crisper' than the previous generation and provided for smooth, very low spatter metal transfer considered essential to obtain consistent, defect-free girth welds in the X100. The wire feeder and control pendant for each power source were remote from the power supply, allowing flexibility in equipment set-up. This is an advantage considering the small space inside pipeline welding 'shacks'. The power supply also allows inductance and resistance levels to be set appropriate to the length/diameter of welding power and work return cables. Cable lengths of 25 m, as used in the X100 trials, are typical of pipeline welding and the resultant voltage drop (resistance) and current rise/fall rates (inductance) can significantly affect the pulse shape and hence metal transfer. Appropriate waveform modifications can be set automatically by the power source once a datum has been established on the initial equipment set-up.

Figure 7.1 Fronius TransPuls Synergic Synchronised Tandem Welding Power Sources

Tie-in and repair procedures.
The tie-in and repair welding procedure trials on X100 utilized an ESAB Aristo®[8] 2000 (power source LUD 450W, dual drive wire feeder MEK 44C) multi-process welding power unit Figure 7.2). This is an inverter based power supply, capable of 360A at 100% duty cycle of 10 minutes and can be used for DC welding with GMAW, GMAW-P, SMAW or GTAW The standard synergic curves, preset in the machine and operating in DC electrode positive mode, were used by WERC for both rutile flux-cored wire and the solid wire X100 welds, The Aristo® 2000 was set with identical short-circuiting welding conditions as per the internal welder, with the torch placed on a SAW column and boom for easy access/control within the pipe. For SMAW the polarity and current type were set appropriate to the electrode.

To develop the repair welding procedures, a simulated repair groove was prepared by arc-air gouging through half to full pipe wall thickness, prior to grinding a conventional 60° included angle ready for the repair weld. It was found necessary to use an AC transformer for the root/hot pass of the full thickness SMAW/FCAW-G X100 repair weld to avoid the occurrence of considerable 'arc blow' when using DC in this situation. Arc-air gouging and/or grinding can introduce considerable magnetism into the bevel. A Migatronic TIG Commander®[9] 400 AC/DC power source providing 295A at 100% duty cycle of 10 minutes was used for both SMAW weld repair runs in X100.

Figure 7.2 ESAB Aristo 2000 Power Source used for Tie-In and Weld Repair Procedures

7.4 Pipe Bevel Preparation Equipment

WERC used two CRC-Evans pipe facing machines for 30 and 36 in OD X100 pipe with the associated mains powered hydraulic pumping unit.· Serimer-Dasa prepared bevels utilizing their own proprietary in-house equipment.

7.5 Internal and External Pipe Welding Equipment

Cranfield WERC utilized a six-head internal pipe welding machine (IWM) shown in Figure 7.3, loaned, set-up and operated by CRC-Evans for clamping and internally welding the root run in

[8] Aristo® is a registered trademark of ESAB Aktiebolg Corporation, Box 8004, Goteburg Sweden 40277.
[9] Commander® is a registered trademark of Lincoln Global Inc., 1200 Monterey Pass Road, Monterey Park CA 91754

the 914 mm (36 in.) OD X100 pipe. Later in the programme internal GMAW root welds were made on X100 via rotated pipe rather than with a conventional internal pipe-welding machine as shown in Figure 7.4.

A CRC-Evans P100 welding bug and band system was used for all single wire and initial tandem wire X100 welding trials at Cranfield WERC. Figure 7.5.

As a result of using of pulsed welding power supplies in both cases, torches with their associated 3 or 4 m power and gas leads replaced the original CRC torch set-up (designed for remote welding power only). Some other modifications to equipment were made to optimize welding performance and this included removal of the wire-feed motor and reel holder assembly on the bug as these were both superfluous to requirements. The travel motor gearbox was changed when required to suit the given process type. Operation of the bug involved manual adjustment of contact tip to work piece distance (CTWD), groove tracking and travel speed, all via knurled adjustment wheels on the bug. Wire feed speed and arc on/ off were controlled from the power source.

Figure 7.3 CRC-Evans Internal Clamp/Pipe Welding Machine

Figure 7.4 Rollers, Column and Boom set up for Internal Root Welding Trial with X100

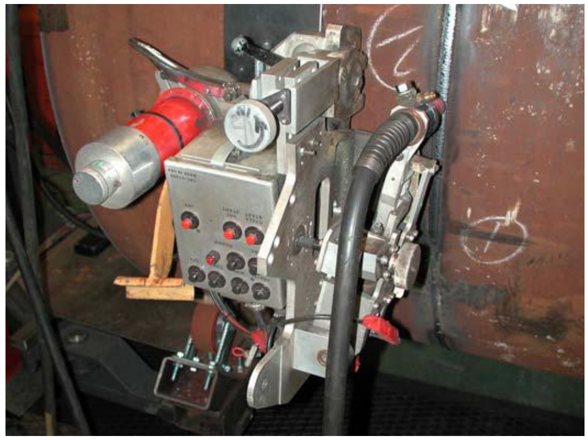


Figure 7.5 CRC-Evans P100 Welding Bug used for Single and Initial Tandem Welding of X100

The tandem wire procedures initially used the same CRC bug, but with increased oscillation rate due to the high travel speeds required of the process. The water-cooled version of the tandem torch shown in Figure 7.6 superseded the air-cooled version early on in the development trials in order to conduct the high peak current over the groove lengths being welded in each single run.

Figure 7.6 Water Cooled Tandem Torch Developed by Cranfield WERC for X100

The Cranfield water-cooled torch is heavier than the original CRC design and requires greater rigidity in the torch fixing location on the bug. The RMS welding systems MOW II bug was capable of holding two WERC tandem torches and allowing independent control of each torch head Figure 7.7. Although the photo shows two tandem torches, the work on X100 utilized only a single tandem torch. In a similar manner to the single wire welds, power source and wire feed drives for tandem wire welds were independent of the welding bug. Pre-programming of a given weld pass was performed, with joint tracking and contact tip to work distance (CTWD) was manually adjusted during the weld pass. Wire feed speed was the only parameter set on the power supply.

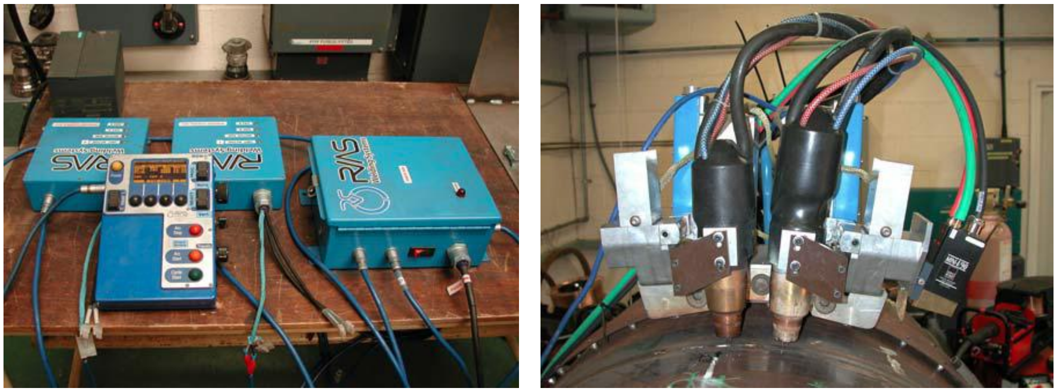


Figure 7.7 RMS MOW II Welding System Control Switching Boxes and Dual Torch Bug with Cranfield WERC Tandem Torches

The Cranfield WERC tandem-wire torch used for welding trials on X100 provided the following features.

- complete electrical isolation between the individual contact tips
- water-cooling of the gas shroud.
- two shroud lengths were manufactured
- minimizing the shroud/pipe surface gap for each weld layer thereby optimizing gas shielding.
- heavy duty torch leads to conducted arc heat via the contact tips, (disadvantage - added weight).
- wire separation of 4-6 mm at CTWD

In separate welding procedure developments on X100, Serimer-Dasa used their Saturnax 5 dual torch welding system and band in a similar manner to that of the WERC. A remote pendant allows the welder to adjust similar parameters as mentioned above but, from the best possible position; usually in front of the leading arc at all times. A given weld pass can be pre-programmed and, in conjunction with the power source, will then deliver all of the required parameters. The bug shown in Figure 7-8 has a fixed distance of 50 mm between the torches; the actual procedures developed necessitated the use of varying torch spacing in order to obtain the required mechanical properties, but this will be discussed in detail later. All of Serimer-Dasa’s test welds were made with a copper backing system placed within the ID of the pipe, such that deposition of all welding passes was from the outside of the pipe only.

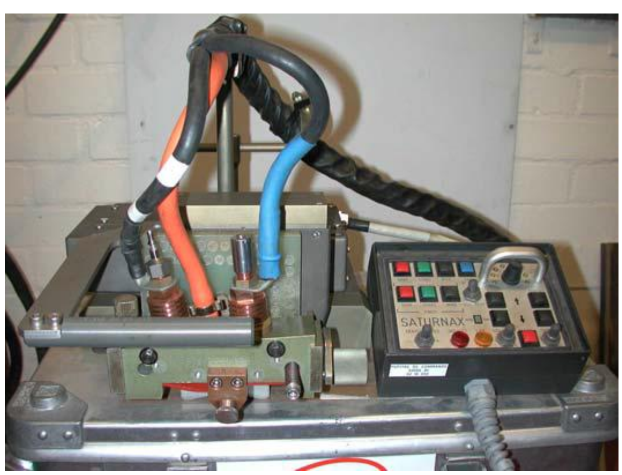


Figure 7.8 Serimer-Dasa Saturnax 5 Dual Torch Welding Bug and Controller

7.6 Target Girth Weld Metal Mechanical Properties

The transverse yield and tensile values were obtained from pre-production X100 pipe used for welding procedure development. Although the SMYS of the pipe is 690 MPa, the actual values will generally be higher, so it is necessary for the weld metal to overmatch the pipe SMYS by 120 MPa, resulting in a weld metal minimum 0.2% proof strength requirement of 810 MPa. Although a 120 MPa overmatch may appear high, it may not always guarantee that the girth weld metal yield strength will overmatch that of the parent pipe in the transverse direction as shown by Table 7.10.

Table 7.10
Selecting Weld Metal to overmatch the transverse yield strength of X100

Pipe Standard/ Weld Metal	**Yield strength,** $R_{t0,5}$ MPa (psi)		**Tensile strength,** R_m MPa (psi)		**Ratio** $R_{t0,5}/R_m$ maximum
	minimum	maximum	minimum	maximum	
ISO 3183/ API 5L L 690M / X100M	690 (100 100)	840 (121 800)	760 (110 200)	990 (143 600)	0,97
CSA Z245.1 Grade 690	690 (100 100)	825 (119 700)	760 (110 200)	970 (140 700)	0,93
Weld metal (idealised)	810 (117 500)	860 (124 700)	N/S	N/S	N/S

A significant increase in strength usually occurs when plate is manufactured into pipe and, coupled with the complex TMCP and relatively lean alloying, presents a challenge to the steel maker and pipe mill to keep the yield strength within a 120 MPa range.

In order to avoid weld metal of excessively high yield (proof) strength, a range of 810 to 860 MPa was considered optimum for the Cranfield development work, during the course of which, Canadian Standard CSA Z245.1-02 was published. [33] This specifies a pipe Grade 690 for which the minimum $R_{t0.5}$ is 690 MPa and maximum $R_{t0.5}$ is 825 MPa with minimum and maximum UTS of 760/970 MPa and maximum Y/T ratio of 0.93. Shortly afterwards, ISO 3183:2007 and the 44th edition of API 5L were published in which the upper limits of the yield and tensile strength were marginally higher than in the Canadian standard.

Although a weld metal under match of 15 MPa or 30 MPa (compared with pipe of the CSA and ISO standards respectively) is possible, any increase from the 810 MPa min. 0.2% proof strength will reduce the yield to tensile ratio of the weld metal with consequent deleterious effects. However, presuming that the $R_{t0.5}$ values from a given pipe lot coupled with the all-weld metal $R_{p0.2}$ values both follow Gaussian normal distribution curves, a substantial overlap should occur thus limiting the potential weld metal under match.

Yield to tensile ratios of the weld metal are likely to fall within 0.90 to 0.95 based on previous results; assuming a maximum allowable ratio of 0.96 results in a minimum ultimate tensile strength of 844 MPa.

The lack of standards for the welding of X100 alongside very limited data from previous weld procedure tests implies that any criteria for toughness (impact and CTOD) and hardness levels have yet to be specified. Extrapolating from existing standards would result in average impact toughness levels of 60-70J and minimum individual values of 50-55J at the design temperature. A further reduction (i.e. more negative) test temperature for impact testing is often used for specification purposes due to the limited constraint effects present in a Charpy specimen. CTOD toughness levels are much harder to determine, and, on an extrapolation basis, (BS 4515:1984), specified levels of 0.30 mm+ would not be uncommon for 762 mm (30 in.) O.D., 20 mm w.t. X100 pipe, taking into account the likely operating pressures and flaw sizes. From the work conducted it is considered unlikely that levels this high will be consistently achieved; more realistic values being 0.15 to 0.20 mm CTOD. Work still needs to be performed in this area to justify the required values. CTOD values, obtained at minus 10°C in the X100 welding procedure tests provide some background data for future specifications.

Hardness levels for the weld metal will be high (compared with existing standards) and this can be expected through the relationship of strength and hardness; if one increases the other will follow suit. HAZ hardness is set at 350 HV10 maximum (non-sour service BS 4515-1:2000). Weld metal hardness levels are likely to be between 280 and 350 HV10 commensurate with a 810 MPa minimum yield [6]. It therefore appears reasonable to set maximum hardness levels throughout at 350 HV10 for X100. Levels above this would indicate the onset of brittle microstructures and consequent deleterious effects on toughness.

7.7 Welding Procedures

Narrow-gap girth welding was performed in the ASME IX 5G position using either single or dual torch (Serimer-Dasa) or single and tandem torch (WERC) mechanized welding equipment. Typical joint preparations for each narrow gap type are as shown in Figure 7.9.

Welding was performed solely from the outside of the pipe with the Serimer procedures, whereas the WERC utilized procedures featuring both internal and external weld deposition. A six-head CRC internal welding machine (IWM) or conventional welding machine with an AWS 5.18 ER70S-6 wire (0.9 mm) was used to deposit the root run in the internal/external welds, whilst a copper backing bar was employed with the all-external procedures (the same consumable throughout being used in the latter case, except for the root run of the Serimer welds (ER70S-6)).

Typical welding procedures used to manufacture the various trial welds may be found in

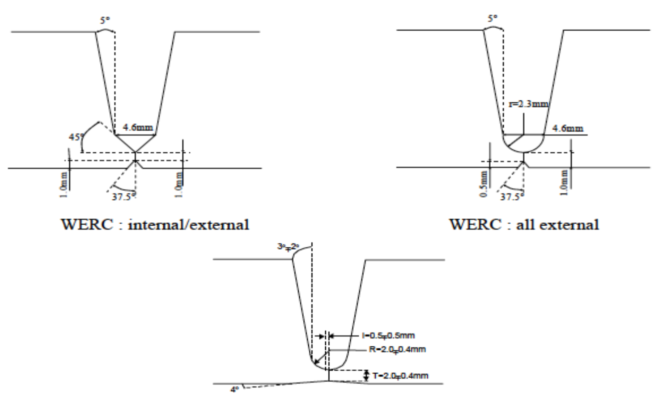


Figure 7.9 Narrow-gap weld preparations for welding procedure development and typical of girth welding preparations for field welding of X100

Hudson’s thesis [65]. Serimer-Dasa used short-circuiting (dip) transfer that is their standard welding mode for the dual-torch welds alongside dip and pulsed procedures for single wire welds.

The WERC used pulsed transfer for both single and tandem welds, for which synergic curves were developed for both 0.9 and 1.0 mm diameter wires. Much effort was expended to obtain concave/ flat profiles in the 5 to 6 o'clock position and it was necessary to reduce the narrow gap bevel width to produce an acceptable profile. The tandem procedures utilized two Fronius synchronized power sources. The correct balance must be obtained between travel speed and wire feed speed, particularly for the 4:30 to 6 o'clock sections to optimize deposition and weld profile. The pulsed waveform details for the Lincoln and Fronius power sources are recorded in Hudson's thesis. [70]

Preheat and inter-pass levels of 100/130°C were maintained for all tests. The BS EN 1011-2:2001 standard [72] for the welding of ferritic steels was used for guidance for avoidance of hydrogen cracking (as per Annex C3 of the standard) which was developed from experience with low alloy high strength steels. The weld metals and base materials fall within the scope of alloy concentrations applicable. However, preheat calculations were based on the CET of the weld metal rather than the pipe (see tables 7.2 and 7.3). Calculated values from the trial test weld metals fall within 50 to 80°C (assuming 2 ml diffusible H_2/100g WM, 19.05 mm WT pipe and a heat input of 0.4 kJ/mm). Therefore adopting 100°C preheat allowed for a conservative approach compared with other procedure data.

Tensile and impact toughness measurements and some weld metal chemistry analyses and hardness traverses were taken from the trial welds. This process continued at the WERC and Serimer-Dasa [70] until the required properties were attained with suitable consumables and welding processes the individual property measurements for each welding process variant being given in Tables 7.11 to 7.24.

It should be stated that the alloys were chosen purely for their chemistry; no preference was given to a particular manufacturer, and chance dictated which manufacturer was selected for the given alloy when it was duplicated.

Several low load (HV2.5) hardness traverses were conducted in several Serimer welds to examine the HAZ of the base material. It was decided to concentrate on the use of two welding consumables; one which just overmatched the yield criteria, alongside one which would adequately overmatch the parent yield strength. Serimer-Dasa chose Thyssen Union MoNi (1Ni 0.4Mo) and the WERC selected Oerlikon Carbofil HT (0.5Ni 0.5Mo 0.5Cr) as the wire that would just overmatch for dual torch and single torch respectively. Bohler X70-IG (1.3Ni 0.25Mo 0.25Cr) was selected as the consumable that adequately overmatched for the dual torch welds and ESAB Spoolarc 120 (2.5Ni 0.5Mo 0.4Cr) was selected for single torch welds. At this point in the programme Serimer-Dasa had settled on using 100 mm torch spacing to attain the required tensile properties. All of these consumables gave impact toughness levels (typically >100J at minus 30°C) from earlier trials.

Complete pipe sections were then welded as per pre-production procedure testing) from which various mechanical tests were obtained. On receipt of a supply of 14.9 mm w.t. 914 mm (36 in.) OD X100 pipe, a further series of procedure tests were made with existing and new consumable types. Serimer-Dasa included Elga Elgamatic 135 (1.5Ni 0.3Mo 0.2Cr) and the WERC chose Oerlikon Carbofil NiMo-1 (0.9Ni 0.3Mo) for dual and single/tandem torch welds respectively. A programme of work conducted by Serimer-Dasa culminated in a torch spacing of 50 mm (typical of existing practice) using Elgamatic 135 and Thyssen Union X85 (1.8Ni 0.5Mo 0.3Cr). Both are relatively highly alloyed consumables (see Table 7.3) but are necessary due to the loss in strength via the closely following second heat cycle. All welding procedures are recorded in Hudson's thesis, Appendix B. [70].

The manual tie-in procedure used vertical-up low hydrogen AWS 5.5 E11018-M electrodes for the root and second pass as opposed to a more conventional vertical-down technique. High strength low hydrogen vertical-down electrodes had been used earlier by WERC but did not produce overmatching properties, so high strength vertical-up electrodes were investigated. The advent of high strength low hydrogen rutile-cored wires provides higher productivity compared with the SMAW equivalent for fill and cap passes. An ESAB wire, OK 15.09 (AWS 5.29 E111T1-G H4) was selected for the procedures and, ESAB recommended restricting the heat input at or below approximately 1.4 kJ/mm to avoid a reduction in strength. A typical API joint preparation was used (30° bevel, 2 mm root gap, 1.5 mm landing) with all welding proceeding in the upward direction. [82]

Repair procedure tests were undertaken to simulate typical defects that may be encountered in pipelay welds. A narrow gap single wire mechanized weld, using Carbofil HT and an identical procedure to the tie-in formed the basis of the test and varying amounts of material were removed to simulate defect excavation. Single/double pass repairs used a mechanically ground groove, whilst larger areas were firstly arc-air gouged and then mechanically ground. SMAW (Filarc 118) and GMAW (Carbofil HT) were used for internal root repairs (single and double pass procedures), with SMAW and FCAW (OK 15.09) used for single pass cap repairs. The root repairs were conducted in the overhead position as it is here that the internal welding machine is most likely to give problems in service. The cap repairs were performed over the 3 o'clock position as lack of fusion defects are most likely to occur here (where the weld metal can run ahead of the arc). A part-penetration FCAW repair was performed to simulate a defect on the fusion boundary halfway through the pipe wall thickness, also at 3 o'clock position. A full penetration repair (essentially identical to the tie-in procedure) was conducted in the 6 to 4 o'clock position. Details of all joint preparations and important welding parameters are included in Hudson's thesis.

The all-weld metal strength of the tie-in procedure did not attain the $R_{p0.2}$ minimum of 810 MPa using semi-automatic FCAW and a conventional API 30° bevel, so further tests investigated reduced bevel angles coupled with semi-automatic and mechanized deposition techniques in order to increase the weld metal strength levels. Another high strength rutile FCAW wire, Oerlikon Citoflux 110, which with the ESAB OK 15.09 wire was used for further tests. A metal-cored wire (Oerlikon Fluxofil M10S) was also used for root run trials in the reduced groove angles. Further details of as-run welding parameters and joint preparations are recorded in Hudson's thesis [70].

7.8 Properties Achieved

7.8.1 Single wire narrow-gap welds

The X100 welding development work by Cranfield (with CRC) and by Serimer Dasa generated a large amount of data and within the remit of this review it is not possible to sample all individual data sets. A more comprehensive understanding of the work can be gained from Hudson's comprehensive thesis. In the course of the development work some welds were made that were unsatisfactory and did not warrant further testing but which served to establish the welding parameter envelope for each process. The following results shown in Table 7.11 are summarized from a larger number of single wire narrow gap girth welds that were worth comprehensive mechanical testing and which prove the mechanical properties that can be obtained in X100 girth welds.

Table 7.11
All-weld tensile results of single wire mechanized GMAW girth welds in X100

Weld	$R_{p0.2}$	$R_{t-.5}$	R_m	YS/TS	Elong %
Mo-Ni	886	719	964	0.92	17.5
Mo-Ni	911	882	982	0.93	16
Spoolarc® 120	971	927	1017	0.95	15
Spoolarc® 120 (TS 6 Root)	883	855	934	0.95	16
Carbofil HT	853	834	900	0.95	10
Carbofil HT	807	809	865	0.93	19.5
Carbofil HT (TS 6Root)	791	792	833	0.95	14.9

A superficial analysis of the above results (and the more comprehensive set of results in the thesis) serves to demonstrate that significant variation of mechanical properties can occur in nominally similar welds made with the same consumable and/or that use of a lower alloyed wire such as K-Nova (TS 6) for the root run can result in a lower strength (presumably by dilution) of a weld made using a higher alloy wire such as Spoolarc or Carbofil for the bulk of the weld. This underlines the sensitivity of the welding procedure to the effects of minor variables.

Hardness measurements (Table 7.12) made on the same welds indicate a similar variation even when the same welding wire is used for different welds. At the girth/longitudinal seam weld intersection significantly higher hardness values can be experienced, attributable in part to the fact that the alloy content of wires used for both the girth and seam welds is higher and that a high cooling rate from the mechanized GMAW girth welding is experienced.

Table 7.12
Summary of hardness of single wire mechanized GMAW girth welds in X100

Weld	Weld Root Hardness HV10		Weld Cap Hardness HV10	
	WM Max	HAZ Max	WM Max	HAZ Max
Mo-Ni	287	279	345/351*	279/317*
Mo-Ni	290	290	330	271/370*
Spoolarc® 120	339	339	339/380*	274/333*
Spoolarc® 120 (TS 6 Root)	271/268*	302/348*	351/339*	332/366*
Carbofil HT	264/282*	302/304*	302/309*	279/304*
Carbofil HT	292/285*	274/304*	270/297*	281/319*
Carbofil HT (TS 6Root)	260/363*	287/348*	309/319*	274/351*

* Higher HV figure relates to girth/seam weld intersection

The Cranfield work also provided an indication of the toughness of X100 girth welds made by the single torch techniques. The values shown on Table 7.13 are selected averaged examples and some low individual values were encountered. Despite some sporadic low values, the average Charpy values are high at -40°C and some remain high at -60°C.

Table 7.13
Summary (example) Charpy values of single wire mechanized X100 girth welds

Weld	CV (J) -20°C Ave		CV (J) -40°C Ave, J		CV (J) -60°C Ave	
	Weld Root	FL Root	Weld Root	FL Root	Weld Root	FL Root
Mo-Ni	201	223	156	153	112	43
Mo-Ni	215	215	191	66	170	66
Spoolarc 120	-	-	212	47	-	-
Spoolarc 120 (TS 6 Root)	180	158	189	117	181	121
Carbofil HT	109	171	105	32	86	166
Carbofil HT (TS 6Root)	93	160	55	135	58	109

The results of Crack tip opening displacement (CTOD) tests carried out at -10°C in weld metal and HAZ of the single wire girth welds are shown in Table 7.14 and, with the exception of some individual values are not untypical of values obtained from other weld metals used for lower strength steels such as X65 – X80.

Table 7.14
Summary (example) CTOD values of single wire mechanized X100 girth welds

Weld	Weld metal CTOD (mm) -10°C			HAZ CTOD (mm) -10°C		
Mo-Ni	0.12	0.15	0.19	0.20	0.40	0.22
Mo-Ni	0.23	0.23	0.25	0.38	0.39	0.33
Spoolarc® 120	0.096	0.16	0.12	0.18	0.095	0.21
Spoolarc® 120 (TS 6 Root)	0.20	0.26	0.31	0.43	0.36	0.34
Carbofil HT	0.16	0.15	0.17	0.23	0.27	0.21
Carbofil HT (TS 6Root)	0.27	0.24	0.25	0.25	0.42	0.38

Table 7.15
All-weld tensile results of dual torch mechanized GMAW girth welds in X100

Weld	$R_{p0.2}$	$R_{t-.5}$	R_m	YS/TS	Elong %
Bohler X70 -IG	841	840	887	0.95	16.8
Bohler X70 -IG	847	845	878	0.96	18.5
Bohler X70 -IG	884	883	929	0.95	16
Thyssen MoNi	835	836	881	0.95	19
Thyssen MoNi	856	862	898	0.95	17.7
Thyssen MoNi	817	816	862	0.95	17.2
Thyssen MoNi	836	-	874	0.96	17
Elgamatic 135	793	-	840	0.94	17
Elgamatic 135	800	717	870	0.92	16.5
Elgamatic 135	776	769	845	0.92	15.5
Thyssen Union 85	860	823	949	0.91	12.5
Thyssen Union 85	825	800	904	0.91	18.5

Table 7.16
Summary of hardness of dual torch mechanized GMAW girth welds in X100

Weld	Weld Root Hardness HV10		Weld Cap Hardness HV10	
	WM Max	HAZ Max	WM Max	HAZ Max
Bohler X70 -IG	292	287/306*	299/322*	270/325
Bohler X70 -IG	279	260/312*	312/297*	317/363*
Bohler X70 -IG	274/314*	270/302*	322/319*	274/330*
Thyssen MoNi	285/292*	274/306*	319/311*	274/309*
Thyssen MoNi	270/283*	262/297*	304/292*	262/342*
Thyssen MoNi	304/279*	281/270	315/297*	281/270*
Thyssen MoNi	255/281*	268/291*	304/285*	283/336*
Elgamatic 135	260/270*	268/301*	302/299*	270/339*
Elgamatic 135	268/285*	272/336*	342/319*	306/360*
Elgamatic 135	292/283*	264/311*	314/318*	266/351*
Thyssen Union 85	311/306*	279/314*	357/357*	317/363*

* Figure relates to hardness at girth/seam weld intersection

7.8.2 Dual torch narrow gap welds

The following examples shown in Table 7.15 of results from dual torch welds made in X100 demonstrate that a minimum weld metal yield strength ($R_{p0.2}$) of 810 MPa is generally achievable but in some cases with a small safety margin and, in a few instances, falling short with values below 800 MPa. Note should be taken of the tensile elongation figures which in most cases exceed 15%. Although the detail of this table does not include the coded identity of the parent X100 pipe, it may be assumed that some variation in tensile properties between welds made from the same consumables results from either varying welding parameters or dilution effects or a combination of both.

Key hardness figures for the dual torch welds were abstracted from a large number of measurements reported in Hudson's thesis and are presented in Table 7.16. A similar argument may hold true for hardness variations as for the tensile figures, i.e. a combination of dilution from different parent metal and variations in welding parameters will affect the properties significantly although, as can be seen from Table 7-8, levels of heat input are generally consistent. It is of note that the maximum weld hardness was not always measured at the girth/seam weld intersection; a fact that cannot be easily explained as the highest combinations of alloy content was in the respective welding wires.

In a manner similar to that of the single wire welds, high levels of Charpy toughness were obtained in the dual torch deposits. With the exception of some isolated lower values, generally high Charpy toughness was maintained in the weld metal down to -60°C. The Charpy toughness of the fusion line was also good down to temperatures of -40°C (again with isolated lower values) but began to tail off at -60°C. Although not evident from Table 7.17 some variation of fusion line impact toughness may be ascribed to different parent pipes used in the tests.

Table 7.17
Summary (example) Charpy values of dual torch mechanized X100 girth welds

Weld	CV (J) -20°C Ave		CV (J) -40°C Ave		CV (J) -60°C Ave	
	Weld Root	FL Root	Weld Root	FL Root	Weld Root	FL Root
Bohler X70 –IG	171	176	142	184	142	51
Bohler X70 –IG	176	227	171	185	173	127
Bohler X70 –IG	190	59	87	37	60	35
Thyssen MoNi	168	214	168	193	197	95
Thyssen MoNi	157	225	163	127	135	122
Thyssen MoNi	185	95	191	29	135	37
Thyssen MoNi	184	145	177	171	145	74
Elgamatic 135	146	197	139	143	109	95
Elgamatic 135	-	-	133	42	97	33
Elgamatic 135	-	-	179	45	133	29
Thyssen Union 85	-	-	151	183	115	49

CTOD test results on the dual torch welds Table 7.18 indicated generally satisfactory values for the weld metals and for most of the HAZ, although some individual low values were experienced with some of the latter. Such low values may be ascribed more to parent metal and individual welding parameters than to the choice of welding wire since the HAZ CTOD values of other welds made with exactly the same welding wires were considerably higher.

Table 7.18
Summary (example) CTOD values of dual torch mechanized X100 girth welds

Weld	Weld metal CTOD (mm) -10°C			HAZ CTOD (mm) -10°C HAZ		
Bohler X70 -IG	0.20	0.18	0.16	0.37	0.40	0.28
Bohler X70 -IG	0.22	0.33	0.30	0.16	0.17	0.34
Bohler X70 -IG	0.14	0.17	0.21	0.023	0.10	0.050
Thyssen MoNi	0.26	0.15	0.31	0.11	0.38	0.20
Thyssen MoNi	0.17	0.26	0.19	0.42	0.22	0.24
Thyssen MoNi	0.36	0.28	0.37	0.38	0.37	0.11
Thyssen MoNi	0.17	0.20	0.19	0.41	0.36	0.32
Elgamatic 135	0.20	0.20	0.16	0.41	0.34	0.44
Elgamatic 135	-	-	-	-	-	-
Thyssen Union 85	-	-	-	-	-	-

7.8.3 Tandem wire narrow gap welds

The results of all weld metal tensile tests from girth welds made with tandem wire techniques are shown in Table 7.19. In these welds the target minimum yield strength of 810 MPa was comfortably exceeded but, in instances where the $R_{p0.2}$ exceed 900 MPa, it was at the expense of tensile ductility.

Hardness tests on the same tandem wire welds indicated that a 300 HV10 limit could generally be met in the root and HAZ where the weld metal fused with parent pipe but in the girth/seam intersection, the inter-alloying effect of the two weld metals resulted in some high values of hardness that exceed limits of most codes. See Table 7.20. The situation is accentuated in the weld cap area, where weld and HAZ would generally not meet a specified 300 HV10 limit and several values would breach a 350 HV10 limit if this were to be allowed.

Results of Charpy toughness tests on girth welds made using tandem wire techniques indicate a generally satisfactory level of toughness can be obtained in the weld root and fusion line down to -60°C as shown in Table 7.21, although weld metal toughness of welds made with nominally the same consumables can show significant variation when used with different parent metal pipes e.g. pipe compositions as given in Table 7.2.

CTOD test results obtained from a few tandem wire girth welds showed generally satisfactory CTOD values see Table 7.22.

Table 7.19
All-weld tensile results of tandem wire mechanized GMAW girth welds in X100

Weld	$R_{p0.2}$	$R_{t-.5}$	R_m	YS/TS	Elong %
Carbofil NiMo-1 TS6 root	967	962	1004	0.96	14.5
Carbofil NiMo-1 TS6 root	902	901	943	0.96	11.5
Thyssen MoNi TS6 root	942	800	977	0.96	12.5
Thyssen MoNi TS6 root	876	793	926	0.95	18.5

Table 7.20
Summary of hardness of tandem wire mechanized GMAW girth welds in X100

Weld	Weld Root Hardness HV10		Weld Cap Hardness HV10	
	WM Max	HAZ Max	WM Max	HAZ Max
Carbofil NiMo-1 TS6 root	260/363*	294/376*	342/336*	319/373*
Carbofil NiMo-1 TS6 root	245/266*	294/345*	322/325*	319/360*
Thyssen MoNi TS6 root	264/276*	292/348*	380/380*	322/383*
Thyssen MoNi TS6 root	314/309*	297/339*	360/366*	297/342*

* Figure relates to hardness at girth/seam weld intersection

Table 7.21
Summary (example) Charpy values of tandem wire mechanized X100 girth welds

Weld	CV (J) -20°C Ave		CV (J) -40°C Ave		CV (J) -60°C Ave	
	Weld Root	FL Root	Weld Root	FL Root	Weld Root	FL Root
Carbofil NiMo-1 TS6 root	93	160	55	135	58	109
Carbofil NiMo-1 TS6 root	189	239	191	177	173	93
Thyssen MoNi TS6 root	186	219	191	203	169	66

Table 7.22
Summary (example) CTOD values of tandem wire mechanized X100 girth welds

Weld	Weld metal CTOD (mm) -10°C			HAZ CTOD (mm) -10°C HAZ		
Carbofil NiMo-1 TS6 root	0.13	0.15	0.23	0.40	0.30	0.45
Carbofil NiMo-1 TS6 root	0.23	0.18	0.24	0.36	0.42	0.34
Thyssen MoNi TS6 root	0.15	0.14	0.15	-	-	-

7.8.4 Tie-in and repair weld results

The tie-in and repair welds in X100 represented more of an ad-hoc attempt to create procedures for these operations using readily available equipment rather than purpose designed mechanized units that were used for main line girth welds. Also the tie-in and repair procedures were not developed as the result of many systematic trials in the way that the main line girth welds did. The essence of the repair welding technique is flexibility since it must be adaptable to reinstate small to medium lengths of defective girth weld that have been removed by mechanical or thermal gouging and grinding, typically leaving a weld excavation of much less precise dimensions than for mechanized girth welding. The root of the full penetration repair weld is usually best repaired manually by SMAW, in this case with a basic coated SMAW electrode, Filarc 118, then the fill and cap of the repair can be made with the FCAW process, in this case using ESAB OK 15.09 cored wire. A similar technique is needed for tie-in welds where it would be impossible to achieve the necessary precision of weld bevel and fit-up for mechanized GMAW welding and impossible to use an internal line-up clamp. Therefore, the tie-in process must be tolerant to some variation in fit up and operationally flexible to work around external clamping or in-groove tack welding or a combination of both. Therefore there is a strong similarity between techniques used for repair and for tie in welding. Results of all-weld tensile tests on the full penetration repair and the tie-in are shown in Table 7.23 and indicate that the welds produced in this way do not meet the minimum 810 MPa yield strength requirement. Although such welds would be stronger than a pipe meeting only the minimum specified properties of X100, there is a strong likelihood of weld metal under matching (in the transverse direction of the pipe) although the degree of under match versus the longitudinal yield strength of the pipe would be less. Development or identification of an FCAW cored wire producing weld metal with an $R_{p0.2}$ of around 840 MPa, together with sufficient toughness is a technology gap that remains to be addressed.

Table 7.23
All-weld tensile results of full penetration repair and tie-in welds in X100

Weld	$R_{p0.2}$	$R_{t-.5}$	R_m	YS/TS	Elong %
Full Penetration Repair Filarc 118/OK 15.09	724	725	816	0.89	19.1
Tie-in Filarc 118 Root/HP OK 15.09 Fill/Cap	737	733	800	0.92	18.2
	746	731	841	0.90	16.0

Where it has been possible to make hardness measurements on the variety of back-welds, cap repairs, part and full-penetration repairs and tie-in test welds in X100, hardness levels in the weld and HAZ root areas would tend to meet existing code requirements e.g. below 300HV10 or exceed that limit by just a small margin. While results are frequently similar for weld cap and

HAZ hardness, the SMAW single pass cap repair results in high hardness of 387 HV10 in the weld and 330 HV10 in the associated HAZ. See Table 7.24. It is difficult to see these values being acceptable without some form of thermal treatment being applied to reduce these figures.

Table 7.24
Summary of hardness of full penetration repair and tie-in welds in X100

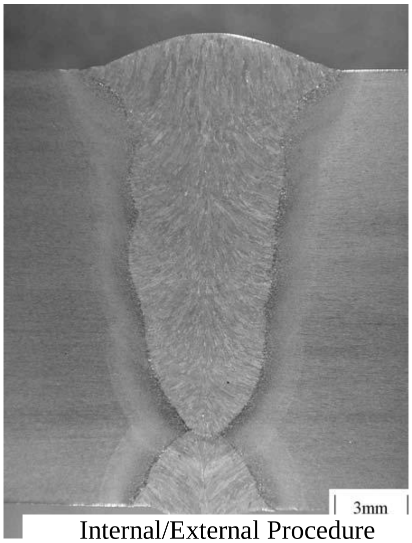
Weld	Weld Root Hardness HV10		Weld Cap Hardness HV10	
	WM Max	HAZ Max	WM Max	HAZ Max
SMAW single pass Backweld	306	317	-	-
GMAW single pass Backweld	283	294	-	-
SMAW two pass Backweld	-	-	317	272
GMAW two pass Backweld	-	-	276	292
SMAW single pass Cap Repair	-	-	387	330
FCAW single pass Cap Repair	-	-	302	272
Part penetration Repair	260	292	319	266
Full Penetration Repair	238	306	339	274
Tie-in	235/249*	243/304*	304/285*	272/302*
* Figure relates to hardness at girth/seam weld intersection				

7.9 Metallurgical Details of X100 Welds

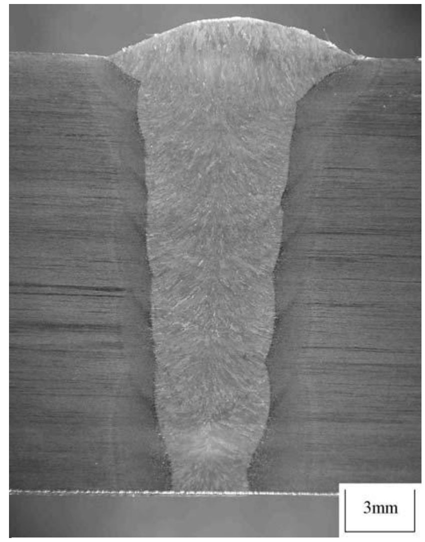
Single Wire GMAW Welds

The quality of X100 weld metal deposited with the single wire GMAW-P techniques can be judged from the example photo-macrographs taken of a Cranfield weld made with an internal root and external fill and an all-external procedure in which the root run is deposited with a backing ring in place as shown in Figure 7.10

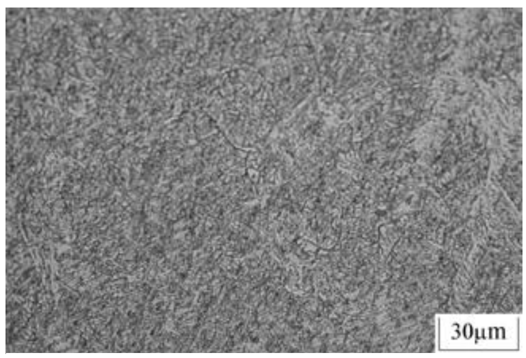
Cap deposits are typically bainitic with acicular ferrite although higher alloy consumables such as 2.5Ni 0.5Mo 0.4Cr produce constituents of a martensitic nature compared with deposits from lower alloy wires such as 1Ni-Mo or 0.5Ni 0.5Mo 0.5Cr that are more bainitic with acicular ferrite. The fine microstructure is typical of low welding heat input and fast cooling rates.



Internal/External Procedure



All External Procedure



Single Wire Cap Weld Microstructure

Figure 7.10 Macro-sections of single torch GMAW-P girth welds in X100 (Cranfield) and typical cap weld microstructure

Tandem wire GMAW Welds

A macro-section of a tandem wire GMAW-P weld from Cranfield shown in Figure 7.11 indicates that the higher net heat input to the weld is manifested in a slightly wider weld i.e. more dilution from parent pipe melted out of the weld preparation and a considerably wider and deeper weld cap. The example shown is of a weld with an internal root and external tandem wire fill.

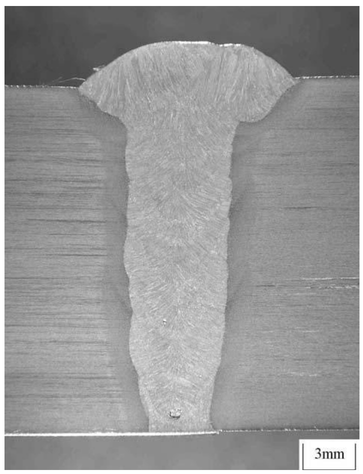
The weld cap metal microstructures are similar to those of the single wire GMAW girth welds being mainly bainitic with varying proportions of acicular ferrite. This is perhaps not unexpected as although the tandem wire provides a higher deposition rate, this is offset by an increased travel speed, so that the net arc energies are similar for both processes.

Dual Torch GMAW Welds

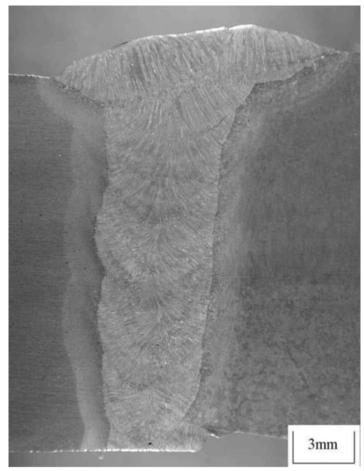
The macro structure of a dual torch girth weld is shown in Figure 7.12 and shows a fine narrow weld profile for most of the section thickness with greater spread and depth of the weld cap than in the single wire welds. This weld was made using dip-transfer (GMAW-S) technique. Where the dual torch girth weld intersects a longitudinal seam in the X100 pipe, mismatch occurs as also shown in Figure 7.12.

A typical microstructure of a cap-weld produced by a dual torch technique is also shown in Figure 7.12. Although torch separation distance may be considered a procedure variable the X100 weld microstructures and mechanical properties were similar irrespective of torch separation over a 50 – 100 mm range. The welding wire alloy contents required to generate the strengths in either case however are considerably different to account for the different weld cooling rates.

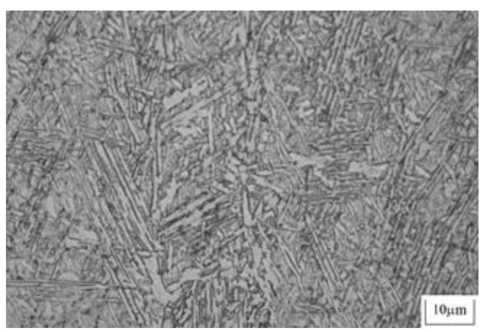
The cap microstructure shown of a dual torch cap weld is typical of most and is a fine acicular structure. The Serimer dual torch welding trials investigated several different welding consumables and two torch spacings of 50 mm and 100 mm respectively but resulted in less variation of microstructure than might have been expected.



Dual torch pipe-pipe girth



Dual torch girth/seam intersection



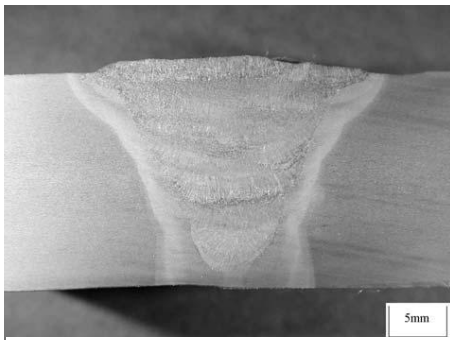
Dual Torch Cap Weld Microstructure

Figure 7.12 Macro-sections and typical cap weld microstructure of dual torch GMAW-S girth weld in X100 (Serimer)

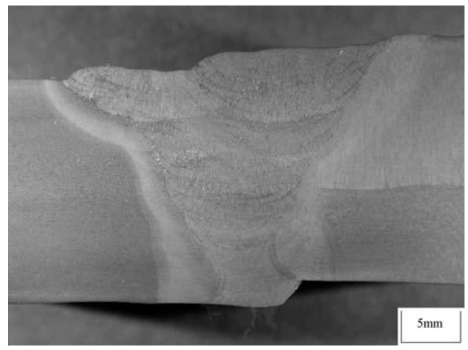
Tie-in Welds made by FCAW Process

Photo macro graphs of tie-in welds taken across pipe-weld-pipe and pipe-girth weld-seam weld section are shown in Figure 7.13 along with a typical weld cap microstructure. Firstly, these welds were deposited in conventional, wider-angle weld groove than the narrow gap girth welds and using the FCAW process. The macrograph of the weld directly between the pipe parents a sound weld but apparently coarser in micro structure than in the narrow gap GMAW welds and this is confirmed by the larger grain size of the FCAW weld cap microstructure. This microstructure reflects the higher arc energy and slower cooling rates inherent in the tie-in welding technique but is also indicative of the lower strength that was measured in the all -weld metal. Attempts by Cranfield WERC to improve on this situation by utilizing a groove of narrower angle and a different FCAW tubular wire (Oerlikon Citoflux 110) in place of the original ESAB Tubrod 15.09 did little to obtain improved strength or microstructure and indicate the limitations of the rutile cored FCAW wires used.

The macrograph of the weld at the girth seam intersection shows considerable misalignment that would probably remain a problem in pipe-lay tie-in welding and the dilution effects of the alloyed weld metals of both the girth and seam may manifest in local microstructural and property variation.



12 o'clock position



Girth/Seam Intersection

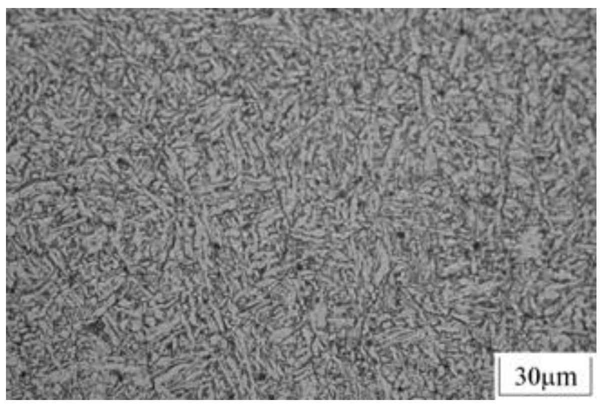
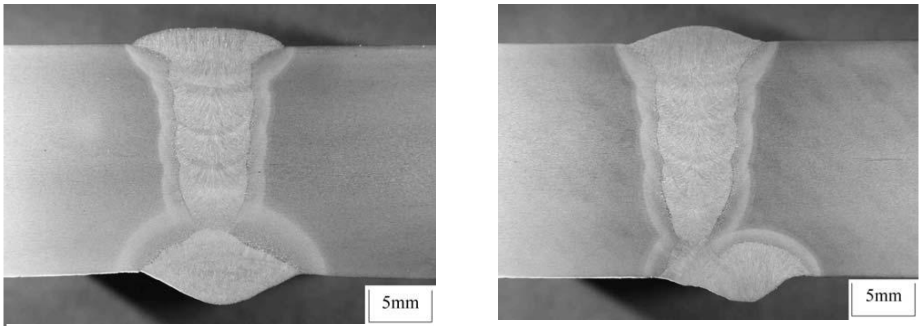


Figure 7.13 Macro sections and typical cap weld microstructure of a tie-in weld made with FCAW-G

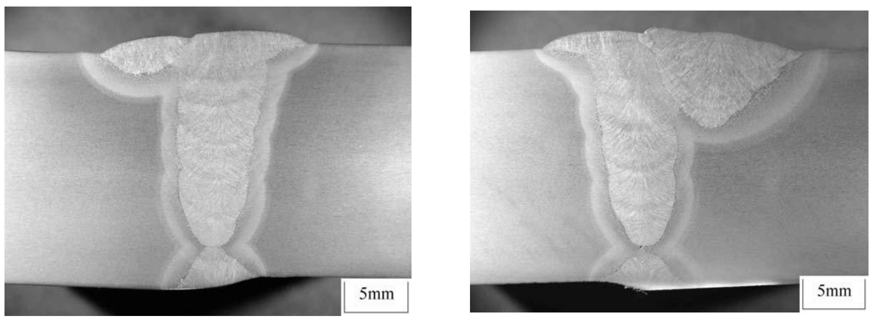
Repair Welds

The photo-macrographs shown in Figures 7.14 through 7.16 show the sections of several weld repair techniques all of which may be needed in practical pipe lay situation for X100. The macrographs demonstrate the practical feasibility of back weld repair by both SMAW (using a high strength basic low hydrogen consumable) and with GMAW.



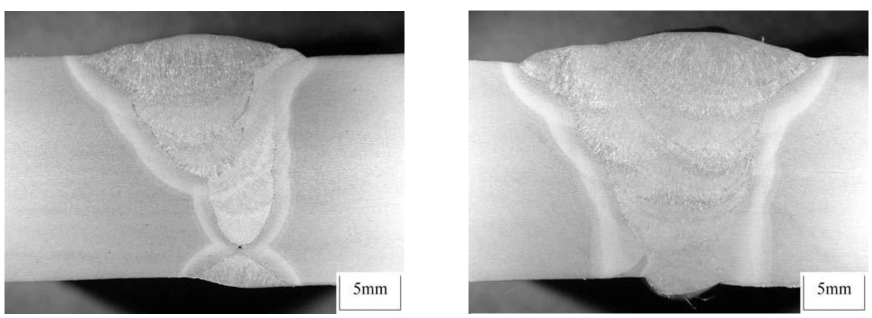
Two pass SMAW Backweld Repair	Single Pass GMAW Backweld Repair

Figure 7.14 Backweld Repair Macro Sections



Single pass SMAW Repair	Single pass FCAW Repair

Figure 7.15 Weld Cap Repair Macro Sections

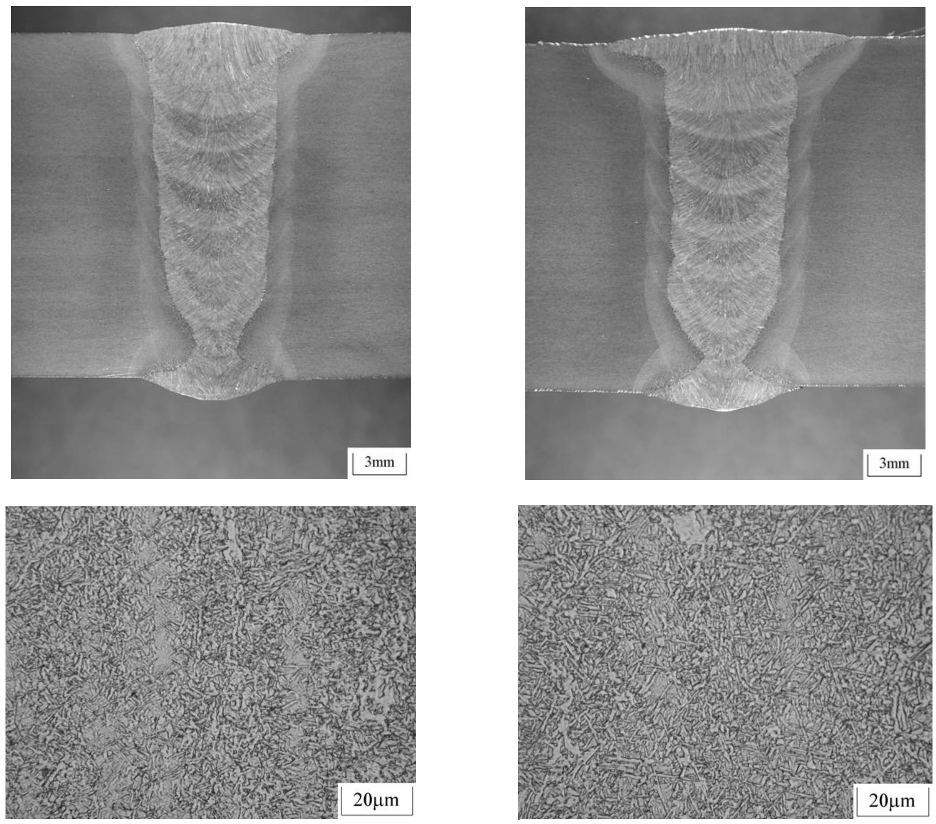


Part penetration FCAW Repair	Full penetration SMAW/FCAW Repair

Figure 7.16 Multi-pass Weld Repair Macro Sections

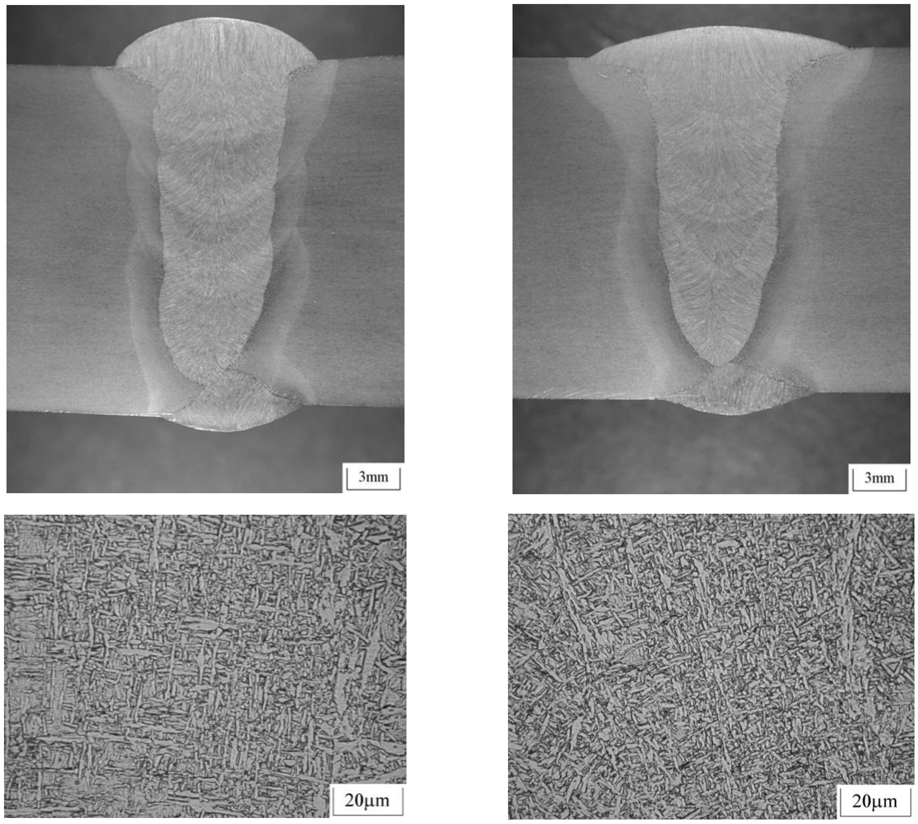
Single pass cap repairs are also feasible with either SMAW or FCAW as shown in Figure 7.15 although the strength of the FCAW all-weld metal cannot be assessed easily from the repair weld alone and cross-weld tensile testing would be the only way to measure the overall strength of the weld (and if fracture occurred in the repair weld or the parent pipe metal). This can in the case of the full penetration repair (Figure 7.16) form which all-weld metal tensile test pieces can be taken.

Figures 7.17 and 7.18 provide an indication of the macro and microstructures of narrow gap GMAW welds made using the single and tandem wire modes and with dual torch and dual tandem modes. In each case it can be seen that sound welds can be made in X100 and that cap-weld microstructures for single, tandem and dual torch were similar. The macrostructure of the dual tandem weld (Figure 7.18) hints at a broader spread of heat at the top of the weld giving greater width of the later fill pass and capping run and a more extensive heat affected zone. Cranfield WERC also conducted systematic preheat trials on test welds that were typical of these with a range from no preheat to 180°C and concluded that a weld metal microstructures ranged from martensitic, through ferrite with an aligned second phase bainite and ferrite with aligned second phase side plate/Widmanstätten structure.



Single wire GMAW　　　　Tandem wire GMAW

Figure 7.17 Process Variant Weld Macro Sections and cap weld microstructures



Dual torch GMAW Dual tandem torch GMAW

Figure 7.18 Process Variant Weld Macro Sections and cap weld microstructures

Summary - Cranfield Trials and Procedure Development for Welding X100

The development work carried out jointly by Hudson in Cranfield with Serimer in France provided a fundamental understanding of the welding variables that would influence the properties of X100 girth welds made under field conditions. The work also assisted in selecting optimum welding consumables from the range available to meet the specified mechanical property requirements. Many full girth welds had to be produced, using several mechanized GMAW-P variants, a range of welding wires, systematic variation of key welding parameters and several sources of parent pipe supply. Early trials often resulted in off-specification welds before the target mechanical properties were achieved.

A key objective was for the girth weld metal to achieve a minimum yield strength of 810 MPa (117 ksi) to ensure that it overmatched the actual yield strength of the parent pipe. Early trials produced weld yield strengths that were either too low or excessively high; the latter often failing to achieve sufficient Charpy toughness. The results of many tests allowed for the influences of key welding parameters to be understood, including welding wire composition, arc energy, dilution (affected by changes in weld bevel details) and even pulse characteristics. Eventually, the tests achieved the aim of a consistent 810 MPa yield strength and acceptable toughness in the weld metals and HAZ. It seems that perhaps a higher degree of precision is needed in the control of welding variables for X100 to achieve the required balance of strength and toughness in the girth weld metal than in similar operations for pipe of lower grade. This imposes constraints on the use of the welding process in order to obtain sound, defect free welds but if this is done, there appears to be no insurmountable problem in achieving quality weld metal with the required yield strength overmatch.

The Cranfield work went on to demonstrate that the required girth weld properties could be achieved with three variants of mechanized GMAW-P welding; single wire, tandem wire and dual torch; the latter variants paving the way to greater field productivity. Again, welding wire selection was optimized. Some work was done with dual-tandem welding (the Cranfield CAPS system) to further enhance productivity although it is uncertain if this variant has yet been used successfully in the field.

The Cranfield development provided useful pointers in respect of the following variables.

- Weld bevel geometry which is effectively an "essential variable" as uncontrolled variation for a given welding wire, procedure and parent pipe can markedly affect the weld metal properties.
- Torch spacing in dual torch techniques similarly affects the weld metal properties.
- Welding consumable selection for welding X100 requires care. Solid GMAW wires of the low alloy type are required for X100 but the same wire can result in weld metals having very different properties when used with different variants of the mechanized GMAW process. This implies that contractors should qualify precise combinations of process, welding wire and parameters for field use. A wire performing well with single torch GMAW-P may not perform as well with dual torch or dual tandem operations or vice versa.
- Preheat and inter-pass temperature variation were shown to affect yield strength, with decrease of preheat/inter-pass temperature resulting in a direct increase of strength in a near linear relationship, In the extreme situation, such variation could exceed the proposed yield range. This highlights the need for close control of the welding operation.
- The specific pulsed waveform of the mechanized GMAW-P power source can also be an essential variable as this is critical for stable weld metal transfer in the narrow welding groove. The waveforms were considered specific to the given power supply and cannot be arbitrarily transferred to another power source without re-tuning. This affects the girth welding of X100.

Tie-in welding requires a different technique as mechanized GMAW cannot be used. The FCAW-G process was used and successfully overmatched the 690 MPA SMYS of the parent pipe but with much less margin than the GMAW-P narrow gap welds. The rutile-cored FCAW wires offer excellent weldability and field-handling but metallurgically cannot attain the higher strengths. This is a technology gap for which development is necessary.

Repair procedures in X100 were developed successfully and should be suitable for field use, providing that careful attention is paid to heat input/cooling rate and consumable selection.

After welding, the X100 parent pipe materials exhibited no significant problems of high hardness or poor toughness in the HAZ. In fact, a small amount of HAZ softening was noted in some welds.
Special attention is required for the girth/longitudinal seam weld interaction for some X100 steels, due to the high alloy content of the seam weld and inter-weld dilution, the resulting weld metal can sometimes exceed 350 HV10.

Target mechanical properties were established for field welding under strain-based design conditions.

The Cranfield development established ground rules for the field welding of X100 line pipe, allowing pipeline operators to proceed with the first installations of TMCP X100 line pipe in gas transmission pipelines in Canada and for an operational test trial in UK.

8. Field Welding Experience - Applying the Technology

8.1 TransCanada Pipelines X100 Pipeline Projects

8.1.1 General

TCPL have invested significantly in the development and welding of X100 line pipe since the late 1990's. In addition to sponsoring fundamental field welding development in co-ventured projects with BP at Cranfield University and elsewhere, TCPL have taken the fabrication, welding and pipelay techniques to the field in several trial projects and, in doing so, have gained valuable experience in high strength pipelay technology. TCPL provided technical data which is summarized in this section of this PRCI report. [64] In addition, experience has been gained in welding and pipe-lay of X120 in co-operation with ExxonMobil [29].

The field projects (summarized in section 2.2 of this report) include Westpath Alberta (September 2002), Godin Lake, Alberta (February 2004) Stittsville, Ontario (August 2006). [28, 29, 30, 31, 32, 33, 34]

8.1.1.1 Western Alberta System - Westpath Project Pipelay – Saratoga Section -September 2002

In September 2002, TCPL undertook the first pipeline construction in the modern X100 pipe when a 1 km length of 1219 mm (48 in.) diameter x 14.3 mm wall thickness X100 was laid in Alberta. [29] The pipe was manufactured by NKK (now JFE) of Japan and was supplied with a fusion bonded epoxy coating. The pipe was specified to CSA Z245 1-02 Grade 690, supplemented with a TCPL purchase specification which called up tighter tolerances than the CSA code and restricted maximum carbon equivalent (CE) value to a favourable value of 0.35 although TCPL reported that a product CE of 0.26 was obtained in the pipe supplied. It should be noted that the CE formula of CSA Z 245.1-02 differs from both the CE_{IIW} and the conventional Ito-Bessyo Pcm formulae, so care should be taken when comparing materials from different projects based on declared CE values.

It is understood that the formula specified in CSA Z245.1-02 was used to calculate CE and trial calculations based on the composition limits specified in TCPL supplement P-04 suggests a typical CSA CE value of 0.26 is akin to a Pcm value of typically 0.21 or 0.22. If the IIW CE formula is used for calculation from the same pipe composition, the composition limits in Table 8.1 indicates a probable value closer to 0.45, which is fairly typical for X100 used elsewhere.

Table 8.1
Typical Chemical Composition of Westpath X100 Pipe

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	V+Nb	Ti
CSA Z245.1-02	Max 0.26	Max 0.50	Max 2.00	Max 0.030	Max 0.035	NS	NS	NS	NS	Max 0.11	Max 0.11	NS	Max 0.11
TCPL Spec	Max 0.07	Max 0.35	Max 1.95	Max 0.020	Max 0.001	Max 0.30	Max 0.30	Max 0.30	Max 0.30	Max 0.06	Max 0.02	Max 0.08	0.004 0.020
Ladle	0.06	0.10	1.87	0.009	0.001	0.27	0.14	0.03	0.22	0.05	0.00	0.05	0.009
Product	0.05	0.09	1.87	0.009	0.001	0.28	0.14	0.03	0.22	0.04	0.00	0.04	0.008

Figures in the above table suggest that the specified composition limits in Z.245.1-02 are too broad for optimum weldability and toughness or to meet specified property requirements and have had to be significantly modified by TCPL's pipe specification. In fact, X100 (Grade L690) is now more appropriately specified in ISO 3183:2007 and the harmonized 44^{th} edition of API Specification 5L, where the carbon content of X100 is limited to 0.10 w.t. % maximum.

The specific installation of the X100 was in the Western Alberta System Mainline loop # 2 (Saratoga Section) in Alberta and comprised 20.9 km of 1219 mm (48 in.) diameter X80 and the 1 km of X100. Tensile properties of the Westpath X100 pipe are as shown in Table 8.2. As can be seen the pipe material met the X100 requirements of the CSA standard Z245.1-02 and they also met the requirements of the TCPL pipe specification when qualified with round bar. The yield and ultimate tensile strengths of 763 and 838 MPa respectively with a Y/T ratio of 0.91 are comfortably within specification. However the flattened strap marginally failed to meet the minimum yield strength requirements of the CSA standard resulting in a much lower Y/T ratio. This situation is not uncommon. It is considered to stem from the Bauschinger effect and has prompted calls in some quarters to standardize on round bar direction tensile testing.

Table 8.2
Tensile Properties of Westpath X100 Line Pipe

	Pipe Body - Transverse								**Pipe Body - Longitudinal**			
	Flattened Strap Specimens				**Round Bar Specimens**				**Round Bar Specimens**			
	YS MPa	TS MPa	Elong %	Y/T Ratio	YS MPa	TS MPa	Elong %	Y/T Ratio	YS MPa	TS MPa	Elong %	Y/T Ratio
CSA Z245. 1-02	690 825	760 970	Min 17.0	Max 0.93	690 825	760 970	Min 11.0	Max 0.93	NS	NS	NS	NS
Actual Average	684	846	27	0.81	763	838	21	0.91	623	801	22.3	0.78

The fracture toughness property requirements for pipe and weld for the Westpath pipe were determined based on a fracture initiation and propagation control plan and the fracture toughness energy values met the specified requirements as shown in Table 8.3. Note that CSA Z245.1-02 only addresses nominal pipe body toughness while CSA Z.662 addresses requirements for fracture initiation and arrest design. For higher pressures and stresses, a full engineering analysis is required.

Table 8.3
Pipe Toughness Properties from X100 Westpath Line Pipe

	Charpy Impact Energy @ -5ºC				**Drop Weight Tear Test @ -5ºC**		
	Body Any Heat J	Body All Heat Average J	Weld J	HAZ J	Energy J	Any Heat % Shear	All Heat Average % Shear
CSA Z245.1-02	40		NS	NS	NS	50	85
TCPL Spec	140	210	75	75	NS	85	90
Average	241		112	122	7781	100	
Minimum	214		98	94	7059	100	
All heat Average		241					100

TCPL implemented a planned programme of training and information prior to the commencement of the project, to familiarize contractors and regulators with X100 line pipe and the necessary refinements required to construction techniques. This programme included welder training and requalification for a changeover from mechanised GMAW in short circuit transfer mode from welding X80 to the mechanized welding with the pulsed GMAW procedures. Welding was carried out by a commercial contractor, Marine Construction Ltd, using CRC-Evans P-GMAW equipment. Details of the mechanized GMAW-P field welding procedures are as summarized below.

- The main Westpath project construction was in 1219 mm (48 in.) diameter x 12 mm wall thickness X80 pipe which was girth welded using a standard short-circuit mechanised welding. A deliberate decision was made to specify the higher strength X100 as 1219 mm (48 in.) diameter x 14.3 mm wall thickness in order to develop longer term requirements for high pressure design. There was no pretence that the higher wall thickness or X100 at all was needed for operational reasons on Westpath.

- All welding procedures were qualified by the contractor and TCPL to meet the relevant CSA Codes and were used for both workmanship and alternative acceptance criteria according to Appendix A of CSA Z662-99 [63].

- The project also tested the field bendability of X100 and although some bending trials had been performed earlier on NPS 36 X100, time did not permit the same for NPS 48. However, field bending proceeded smoothly without problems and no coating issues arose. Pull times were similar to those for X80 but slightly shorter pulls were used to compensate for additional spring-back and overall bends of 1 degree per pipe diameter were achieved.

Further details of the Westpath project can be found in reference [29].

Westpath Mainline Welding - Single Wire PGMAW. [64]

- 1219 mm (48 in.) OD x 14.3 mm w.t X100 pipe from JFE Corporation Japan
- Weld prep: compound angle top bevel, single angle root bevel - precision machined
- Root pass Pulsed GMAW - 8 internal single torch welding heads
- Root pass 0.9 mm diameter Thyssen K-Nova (ER480S-6) deposited internally
- Travel speed 760 mm/min, wire feed speed 9.65 m/min
- Internal line-up clamp with internal welder - removed after completion of root bead
- External welding, two welding head each mounted on a CRC-Evans P200 bug-on-band tractor
- Hot, fill and cap passes: Pulsed single torch GMAW
- Hot, fill and cap passes: 1.0 mm diameter Oerlikon Carbofil NiMo-1 (ER690S-G)
- 5G, downhill, weaved multi-pass
- Polarity DC+
- Max. time lapse root-hot pass 5 mins max, second - fills 60 mins max, to completion 24 hours max.
- Ar/CO_2 shielding gas 75/25 mixture for root, 85/15 for hot, fill and cap passes
- Shielding gas flow rate 35-47 litres/minute (2.10-2.80 cu. metres/hour)
- Preheat 100ºC min Interpass controlled between 100º- 135ºC.
- Hot pass travel speed 1.27 m/min, wire feed speed of 10.1 m/min
- Fill passes travel speed 0.3 to 0.5 m/min, wire feed speed of 10.6 to 11.1 m/min
- Cap pass travel speed 0.25 to 0.57 m/min, wire feed speed of 8.3 to 11.1 m/min.
- Head oscillation specified for each pass
- Arc energy typically 0.3 kJ/mm root, 0.15-0.20 kJ/mm hot, 0.46-1.2 kJ/mm fill and cap
- Power sources: Miller Invision™ 456MP

Procedures were also qualified for repairs and tie-in welding using manual SMAW techniques

Westpath Repairs and Tie-in Welds [64]

- Root pass: Manual SMAW (E55010-G) cellulosic root pass
- Hot pass: 3.2 mm Lincoln LHD100 (E69018-G) hot pass,
- Fill and cap passes (remainder) 4.0 mm BVD 110 LHVD (E72018-G)
- No pipe movement until after completion of hot pass
- 24 hour inspection delay prior to inspection of all shielded metal arc welds
- Only two tie-in welds were required.

It is noted that a high strength cellulosic coated SMAW consumable was used to deposit the root pass but all other passes were deposited using basic coated low hydrogen electrodes. The residual hydrogen content in the root pass is not known. If the hot pass and first fill pass were deposited immediately on the root, the maintenance of preheat and inter-pass temperature increases the diffusion rate of hydrogen although the path for diffusible hydrogen to exit the weld will be greater. The fact that passes, other than the root pass are deposited with low hydrogen electrodes implies that the net hydrogen per unit volume of weld is lower and the additional cross section of weld is better able to resist stresses. Although this technique appears to have given satisfactory results for TCPL on the Westpath tie-in and repair welds, and was retained for tie-in and repair procedures on later projects, the findings of other workers [66] suggest that use of cellulosic coated SMAW for root runs in X100 may incur a higher risk of hydrogen induced cracking.

A summary of WPQT tensile test results are shown in Table 8.4 and indicate that average yield and tensile strengths of all-weld metal from mechanised P-GMAW girth welds were 698 MPa and 815 MPa respectively. These values would comfortably over-match the longitudinal yield and tensile strength of the X100 parent metal and the yield strength from a transverse direction flattened strap test but under match the transverse direction yield strength of a parent pipe round bar tensile specimen. The relatively low average yield strength of the weld metal implies that the K-Nova/Carbofil NiMo-1 combination cannot be used where an overmatch of X100 transverse direction parent metal properties must be guaranteed. Cross-weld tensile strengths ranged from 774 to 825 MPa but in each case the position of fracture was in parent pipe; the fracture mode being ductile.

Table 8.4
WPQT Tensile Results on X100 Line Pipe Girth Welds Westpath Project [29]

Weld/Pipe	Test	YS / 0.2% MPa	TS MPa	Elong %	R of A %	Notes
Main line P-GMAW on X100 14.3 mm w.t. pipe	All weld tensile	678	814	22		
		721	816	25		
	Cross weld tensile CSA Z662		825			Ductile fracture in pipe
			812			Ductile fracture in pipe
			774			Ductile fracture in pipe
			818			Ductile fracture in pipe

Table 8.5
WPQT Charpy Test Results on X100 Line Pipe Girth Welds
Westpath Project [29]

Weld/Pipe	Position	Charpy Energy J @ -5ºC	Charpy Energy J @ -5ºC Average	Shear %
Main line P-GMAW on X100 14.3 mm w.t. pipe	Weld Centre Line	144	153	100
		152		100
		163		100
	HAZ	241	230	100
		230		100
		220		100

Charpy test results are summarized in Table 8.5 and indicate an average CVN energy of 153 Joules at -5ºC at the weld centerline and an average of 230 Joules in the HAZ.

The X100 Westpath welding mainline was completed successfully over a two day period and was inspected using Auto-UT. Weld repair rates were consistent with a normal project start. A few lack of fusion defects required repair, however these were generally restricted to one location in the hot pass/first fill region, and were attributed to a crowned hot pass bead and the inability of the first fill to adequately penetrate into the notch on either side against the original pipe bevel.

Final hydrostatic testing of the pipeline was carried out in early October and the line entered service in November 2002 and has operated ever since. This trial pipe-lay proved that X100 could be welded and laid by a commercial contractor under normal site conditions although the early autumn weather could not be considered as a simulation for the extremes of arctic pipe-lay in winter. This project was essentially a test of constructability and welding rather than an operational trial as the X100 pipe is loaded to a relatively low design factor.

8.1.1.2 North Central Corridor, Godin Lake Project - February 2004 [30]

In February 2004 TCPL proceeded with a second "demonstration" pipeline at Godin Lake in Alberta, Canada. This field test near Slave Lake provided the three major research and development sponsors TCPL, BP and ExxonMobil with a remote setting in which to demonstrate that X100 and X120 could be laid into a pipeline under normal winter site conditions. This work formed part of a larger project (Peerless Lake) which involved laying 17.7 km of NPS 24 X70 pipe in Northern Alberta and the trial "field" construction included a 2.0 km loop of 914 mm (36 in.) diameter x 13.2 mm wall thickness X100 pipe developed jointly by TCPL and BP and a 1.6 km loop of 914 mm (36-in.) x 16.4 mm X120 pipe developed by ExxonMobil.[83]

The 914 mm (36 in.) diameter X100 pipe was ordered to the same specification as the earlier Westpath project with some modifications and was again supplied by JFE Corporation of Japan. Additional testing requirements were included to establish a larger database on the properties of X100. The pipe was ordered with a slightly lower yield strength in the longitudinal direction to maximize the strain based design approach. Tensile properties are summarized as below in Table 8.6. Additional work on the tensile and compressive behaviour was the subject of separate R & D [31]. The results supported the use of round bar transverse direction tensile testing which correlated well with ring-expansion tests.

Table 8.6
Tensile Properties of Godin Lake X100 Line Pipe [29, 31]

	Transverse				**Longitudinal**			
	YS MPa	**TS MPa**	**Elong %**	**Y/T Ratio**	**YS MPa**	**TS MPa**	**Elong %**	**Y/T Ratio**
Minimum	715	789	20.0	0.88	596	763	50.0	0.72
Average	779	851	22.0	0.92	642	816	23.0	0.79
Maximum	820	920	25.0	0.94	669	863	26.0	0.85
Std Dev	28.3	36.6	1.8	0	20	31.2	1.3	0.03
No of Samples	24	24	24	24	24	24	24	24

The Charpy toughness test results are summarized in Table 8.7 and all exceeded the specified minimum requirements which were based on a previous Battelle two-curve approach but modified to take into account a series of full-scale fracture tests on X100.

Table 8.7
Pipe Toughness Properties from X100 Godin Lake Line Pipe [29, 31]

	Charpy Energy (J)@ -5ºC			**DWTT @ -5ºC (Pressed Notch)**	
All Samples	**Body**	**Seam weld**	**HAZ**	**Energy J**	**% Shear**
Minimum	125	90	69	5394	98
Average	236	118	103	6425	100
Maximum	302	152	173	7811	100
Standard Deviation	34.7	16.3	25.1	638.7	0.4
No. of Samples	24	24	24	24	24

Extensive development of welding processes and procedures preceded the Godin Lake project to improve the earlier single wire GMAW-P procedures used on Westpath with the objective of eliminating minor imperfections that occurred in the hot-pass/first fill region. This was achieved and the procedure was fully qualified for use on Godin Lake. A second objective was to implement higher productivity GMAW-P tandem welding on which BP, TCPL and Cranfield University had collaborated over several years. Two systems had been developed; single and dual tandem welding. The tandem process features two wires through one welding head; single tandem utilizing only one head and dual tandem utilizing two heads in a fore and aft arrangement driven by the same tractor. Although both processes were considered for the project, only the single tandem was able to produce a series of qualification welds in time to meet the project schedule. The final procedure qualified and actually used on the project was a hybrid combination of single wire pulsed and single tandem pulsed welding.

TCPL implemented a programme of training and information prior to the commencement of the project, to familiarize the contractor, regulator and welders with the X100 line pipe and the project welding procedures. The programme included welder training and qualification on the single wire, single torch welding procedure as well as extensive training and qualification on the tandem process and equipment. Details of the mechanized GMAW-P field welding procedures are as summarized below.

Godin Lake Mainline Welding - Single Wire PGMAW and Tandem PGMAW. [64]

- 914 mm (36 in.) OD x 13.2 mm w.t X100 pipe from JFE Corporation Japan
- Weld prep: compound angle top bevel, single angle root bevel - precision machined
- Root pass GMAW-P with 8 internal single torch welding heads
- Root pass 0.9 mm diameter Thyssen K-Nova (ER480S-6) deposited internally
- Travel speed 760 mm/min, wire feed speed 9.65 m/min
- Internal line-up clamp with internal welder - removed after completion of root bead
- Hot and first fill passes: Pulsed single torch GMAW - CRC-Evans P260 tractor
- 1.0 mm diameter Oerlikon Carbofil NiMo-1 (ER690S-G)
- Subsequent fill, optional strip and cap passes: Single head GMAW-P Tandem – CRC-Evans P600 Tractor
- 1.0 mm diameter Oerlikon Carbofil NiMo-1 (ER690S-G)
- 5G, downhill, weaved multi-pass
- Polarity DC+
- Max time lapse root-hot pass 5 mins max, second - fills 60 mins max, to completion 24 hours max.
- Ar/CO_2 shielding gas 75/25 mixture for root, 85/15 for hot, fill and cap passes
- Shielding gas flow rate 23-47 litres/minute (1.40-2.80 cu. metres/hour)
- Preheat 100ºC min Interpass controlled between 100º- 150ºC.
- Root pass travel speed 0.76 m/min, wire feed speed 9.6 m/min
- Root pass heat input 0.29 - 0.35 kJ/mm
- Hot pass travel speed 1.27 m/min, wire feed speed of 10.1 m/min
- Hot pass heat input 0.21-0.24 kJ/mm
- Single wire fill pass travel speed 0.46 m/min, wire feed speed 9.8 m/min
- Single wire fill pass heat input 0.53 - 0.64 kJ/mm
- Tandem fill passes travel speed 0.5 to 1.4 m/min, wire feed speed of 7.6 - 9.5 m/min
- Tandem fill pass heat input 0.13 - 0.39 kJ/mm
- Cap pass travel speed 0.40 to 0.80 m/min, wire feed speed of 7.1 m/min.
- Cap pass heat input 0.19 - 0.40 kJ/mm
- Head oscillation specified for each pass
- Power sources; Four Fronius TPS400 Digital power supplies at each welding station.
- 100% UT Inspection to CSA Standard Z662-03
- 100% visual inspection

Godin Lake Repairs and Tie-in Welds [64]

- Root pass: Manual SMAW 4.0 mm (E55010-G) cellulosic root pass. Heat input 0.65-0.76 kJ/mm.
- Hot pass: 3.2 mm Lincoln LHD100 (E69018-G) hot pass. Heat input 0.70-1.70 kJ/mm.
- Fill and split cap passes (remainder) 4.0 mm BVD 110 LHVD (E72018-G). Heat input 0.86 - 2.0 kJ/mm
- First fill pass is full weave; others are split weave
- Preheat 100ºC min Interpass controlled between 100º- 200ºC
- Repair preheat 120ºC minimum for all passes
- Welding direction - vertical down
- External clamp - removal after uniformly spaced rood bead deposition around 50% of pipe circumference
- No pipe movement until after completion of hot pass
- 24 hour inspection delay prior to inspection of all shielded metal arc welds
- 100% visual inspection
- NDT 100% UT or RT to CSA Standard Z662 and TCPL Specifications

Girth welding of the X100 on Godin Lake was carried out by CRC-Evans Pipeline International. The tandem GMAW-P system developed for the pipeline welding industry by Cranfield University under sponsorship by BP and TCPL in the UK, almost doubles the welding speed of the conventional single-arc GMAW process. CRC-Evans used its P-260 and P-600 welding systems to add the loop of X-100 pipe to the existing TransCanada line, and achieved a lower-than-expected repair rate of 3.9%. The SMAW tie-in procedures for X100 were essentially the same as for the earlier Westpath project and consisted of a cellulosic root pass followed by low hydrogen vertical-down welding of hot and fill passes.

Welding of ExxonMobil's sponsored X-120 loop utilized CRC-Evans automated P-260 welding "bug" and a new proprietary wire developed by ExxonMobil. At each girth weld, pairs of computer-controlled P-260 units used GMAW-P. Four P-260 welding stations were employed during the four-day pipelay operation, with crews completing an average of 41 welds a day with an overall repair rate of only 1.41 per cent. Further details of the X120 material and welding procedures remain confidential to ExxonMobil and TCPL.

The project was welded in extreme winter conditions winter with temperatures as low as - 45ºC and the field trials which duplicated actual working conditions were judged to be a success with estimated welding production rates being achieved and both loops being completed at an extremely low repair rate. Positive feedback was received from the welding crews and no issues arose from using the high productivity welding process. All welds were inspected 100% using automatic ultrasonic inspection (auto-UT).

The completed pipeline was installed in the trench in March 2004 without any problems and using just one additional side-boom. Normal cathodic protection is applied to the pipeline which has been in operation since March 2004. This project provided valuable experience and proving trial of full scale X100 and X120 pipe, using conventional and enhanced productivity welding and pipe-laying in a remote location during the severity of a Canadian winter, thus paving the way for arctic use.

Tables 8.8 and 8.9 summarize the tensile and Charpy impact results of the welding procedure qualification tests performed for this project which show reasonable consistency with results of similar tests on the earlier Westpath Project.

Table 8.8
WPQT Tensile Results on X100 Line Pipe Girth Welds Godin Lake Project [31, 64]

Weld/Pipe	Test	YS / 0.2% MPa	TS MPa	Elong %	R of A %	Notes
Main line Tandem P-GMAW on X100 13.2 mm w.t. pipe	All weld tensile	795 841	838 868	24 23		
	Cross weld tensile ASTM A370	733 719	803 807	21 20		Ductile fracture in pipe Ductile fracture in pipe
	Cross weld tensile CSA Z662		858 852			Ductile fracture in pipe Ductile fracture in pipe

Table 8.9
WPQT Charpy Test Results on X100 Line Pipe Girth Welds Godin Lake Project [31, 64]

Weld/Pipe	Position	Charpy Energy J @ -5ºC	Charpy Energy J @ -5ºC Average	Shear %
Main line Tandem P-GMAW on X100 13.2 mm w.t. pipe	Weld Centre Line	152 171 171	165	100 100 100
	HAZ	214 217 192	208	100 100 100

8.1.1.3 North Bay Shortcut, Stittsville /Deux Rivieres Project, August - 2006

In the summer of 2006, TCPL installed some 7 km of X100 line pipe at Stittsville in the Stittsville/Deux Rivieres Project. (Stittsville and Deux Rivieres are two sites on the same pipeline system but around 200 km apart). [32] The Stittsville loop included 5 km of 1067 mm (42 in.) diameter x 14.3 mm X100 SAWL pipe manufactured by JFE and 2 km of 1067 mm (42 in.) diameter x 12.7 mm X100 SAWH pipe manufactured by IPSCO of Regina. Both the JFE and IPSCO pipes were produced to CSA Z245.1-02 Grade 690 supplemented in each case with the TCPL pipe specification. Details of the X100 SAWL pipe composition are as shown in Table 8.10 but no details are available of the IPSCO supplied SAWH pipe steel composition. In contrast to the earlier projects it was noted that one welding procedure data sheet allowed for a CE max of up to 0.37 although others state 0.34. The reference to max CE on welding procedures includes the 0.05 max tolerance allowed by the CSA Z662 code but it is understood that actual pipe CE would have been, 0.32 and 0.29. TransCanada qualifies welding procedures on the highest CE pipe in the order for its projects. The minimum design service temperature is minus 5ºC.

Table 8.10
Typical Chemical Composition of Stittsville X100 SAWL Pipe [32]

Spec	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	V+Nb	Ti
CSA Z245.1-02	Max 0.26	Max 0.50	Max 2.00	Max 0.030	Max 0.035	NS	NS	NS	NS	Max 0.11	Max 0.11	NS	Max 0.11
TCPL Spec	Max 0.07	Max 0.35	Max 1.95	Max 0.020	Max 0.001	Max 0.30	Max 0.30	Max 0.10	Max 0.30	Max 0.06	Max 0.02	Max 0.08	0.004 0.020
Ladle	0.07	0.14	1.81	0.010	0.001	0.26	0.14	0.02	0.21	0.046	0.003	0.05	0.010
Product	0.07	0.13	1.80	0.009	0.001	0.26	0.15	0.02	0.20	0.044	0.003	0.05	0.011

Carbon equivalent calculated according to the CSA Z245.1-05 formula below was specified as 0.35 maximum but actual CE values for each heat were typically 0.27 - 0.29.

$$CE = C + F\left(\frac{Mn}{6} + \frac{Si}{24} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr+Mo+V+Nb}{5}\right) + 5B$$ (where F is a factor depending on carbon content)

Results of tensile tests on the Stittsville X100 pipe were not made available but, given the close similarity of composition to the Godin Lake X100 pipe and the fact that both were made by JFE Corporation, an assumption could be made that tensile properties would be similar. A summary of Charpy toughness properties is given in Table 8.11 and indicate high Charpy energy values and ductile fracture at -5ºC. Drop Weight Tear Tests also conducted at -5ºC demonstrated ductile performance.

It should be noted that the toughness values in Table 8.11 have been selected from one pipe batch only for each type of pipe but are considered as typical of each order. The limited amount of data available indicates that both types of X100 pipe provide high toughness levels in parent metal, seam-weld and HAZ and, in the case of the X100 SAWL pipe show consistently good properties over three projects spanning and a period of 4 years.

The pipelay contractor was Louisbourg Pipelines using CRC-Evans equipment. [64] The mainline girth welding techniques were GMAW/tandem P-GMAW with procedures being qualified for both the SAWL and SAWH X100 pipe materials. A back-weld procedure was qualified using the same power sources, welding consumables and welding parameters as for the main line procedures.

Table 8.11
Typical Pipe Toughness Properties from X100 Stittsville SAWL/SAWH Line Pipe [32]

	Charpy Energy (J) @ -5ºC						**DWTT @ -5ºC (Pressed Notch)**	
	Body		**Seam weld**		**Seam HAZ**		**Energy J**	**% Shear**
	Min	**Ave**	**Min**	**Ave**	**Min**	**Ave**		
Purchase Spec	140	210	50	75	50	75	NS	
Typical set*	283	100	106	75	188	90	9067	100
SAWL Pipe	264	100	105	75	210	100	8924	100
	269	100	107	75	201	100		
Average SAWL	272	100	106	75	200	97	8996	100
Typical set* SAWH Pipe	195	100	255** (OD)		254** (OD)	N/A	6257 7971	100 100
	155	100	300** (ID)		247** (ID)	N/A		
	245	100						
Average SAWH	198	100					7114	100

* Typical CVN test piece set comprises 3 tests; typical DWTT comprises 2 tests
** Single values quoted only.

Root runs for the main line welding were deposited, as in earlier projects, using a CRC-Evans 8-head internal welder in short circuiting mode and a 0.9 mm diameter Thyssen TS-6 K-Nova wire. For the hot and first fill passes, a CRC-Evans P 450 tractor incorporating vertical and horizontal tracking was employed and for this project a change to a 1.0 mm Thyssen NiMo-80 filler wire was made. The remaining fill passes and cap passes were completed using the tandem welding process on the CRC-Evans P 450 units.

Repairs and tie-ins were covered by multiple procedures namely

- GMAW (STT®) Thyssen K-Nova (ER480S-G) root/mechanised FCAW-G (ESAB 15.09) fill and cap

- SMAW (E55010-G) root and hot pass with LHVD Bohler BVD 120 (E82518-G) fill and cap
- Three GMAW/mechanized FCAW-G welding stations were set up for tie-in operations and some tie-in welds were completed using the SMAW procedure.

Stittsville Mainline Welding - Single Wire PGMAW and Single Tandem. [64]

- 1067 mm (42 in.) OD x 14.3 mm w.t X100 pipe from JFE Corporation Japan
- 1067 mm (42 in.) OD x 12.7 mm w.t X100 pipe from IPSCO Regina, Canada
- Root pass GMAW - 8 internal single torch welding heads
- Root pass 0.9 mm diameter Thyssen K-Nova (ER480S-G) deposited internally
- Root pass travel speed 760 mm/min, wire feed speed 9.65 m/min
- Root pass shielding gas flow rate 35-52 litres/minute
- Root pass heat input 0.29-0.35 kJ/mm
- Internal line-up clamp with internal welder - removed after completion of root bead
- Root weld power sources Lincoln DC-400
- Hot and first fill passes: External. Single torch GMAW-P CRC-Evans P-260 tractor
- 1.0 mm diameter Thyssen Union NiMo 80 (ER620S-G)
- Subsequent fill, optional strip and cap passes: Single head GMAW-P Tandem CRC-Evans P-450 tractor
- 1.0 mm diameter Thyssen Union NiMo 80 (ER620S-G)
- 5G, downhill, weaved multi-pass
- Polarity DC+
- Max time lapse root-hot pass 10 mins max, second - fills 60 mins max, to completion 24 hours max.
- Ar/CO_2 shielding gas 75/25 mixture for root, 85/15 for hot, fill and cap passes
- Fill and cap pass shielding gas flow rate 21-28 litres/minute
- Preheat 100ºC min Interpass controlled between 100º- 140ºC.
- Hot pass travel speed 1.4 m/min, wire feed speed of 10.5 m/min
- Hot pass heat input 0.20-0.30 kJ/mm
- Single wire fill pass travel speed 0.46 - 0.56 m/min, wire feed speed 9.5 - 10.6 m/min
- Single wire fill pass heat input 0.44 - 0.73 kJ/mm
- Tandem fill passes travel speed 0.7 to 1.15 m/min, wire feed speed of 7.1 m/min
- Tandem fill passes heat input 0.13 to 0.26 kJ/mm
- Cap pass travel speed 0.35 to 1.016 m/min, wire feed speed of 5.8-7.8 m/min.
- Cap pass heat input 0.15 - 0.78 kJ/mm
- Head oscillation specified for each pass
- Power sources Two (hot pass, first fill) or four (remaining fills and cap) Fronius 3200 digital power supplies at each welding station.
- 100% UT Inspection to CSA Standard Z662-03
- 100% visual inspection

Repairs and Tie-in Welds (GMAW / FCAW) [64]

- Root pass by GMAW restricted to equipment using controlled metal transfer technology (Lincoln STT®)
- Root pass: GMAW 1.2 mm ER480S-G wire Thyssen TS-6 K-Nova. Heat Input 0.50-0.80 kJ/mm.
- Ar/CO_2 shielding gas 75/25. Flow rate 23 - 33 litres/min
- Root pass power source; Lincoln Power Wave® 455 STT®
- Hot pass: 1.2 mm ESAB OK Tubrod 15.09. Heat input 0.68-1.25 kJ/mm.
- Fill and cap passes 1.2 mm ESAB OK Tubrod 15.09. Heat input 0.70-1.30 kJ/mm
- Preheat 100ºC min Interpass temperature controlled between 100º- 200ºC
- Max time lapse root-hot pass 10 mins max, second - fills 60 mins max, cap 2 hours max.
- Welding direction - vertical down
- External clamp - removal after uniformly spaced rood bead deposition around 50% of pipe circumference
- No pipe movement until after completion of hot pass
- 24 hour inspection delay prior to inspection of all shielded metal arc welds
- 100% visual inspection
- NDT 100% UT or RT to CSA Standard Z662 and TCPL Specifications

- GMAW Equipment Lincoln Power Wave® 455 STT® (with specified programme controls)

It is clear from review of individual welding procedures specifications and qualifications records that a high degree of precision is necessary. Some lack of fusion defects were reported at the 12 o'clock position and at the 4.00 and 8.00 o'clock positions, the latter being attributed to the welder operator changing position in readiness for controlling welding at the bottom of the pipe.

Welding procedure qualification tests indicated some variability in all weld metal yield strength where one value of 733 MPa obtained from the qualification of the mainline procedure on the SAWH pipe would not guarantee yield strength overmatching of the weld over the parent pipe in the transverse direction but would almost certainly guarantee an overmatch in the pipe longitudinal direction and would probably not impeded strain based longitudinal design. The all weld tensile tests from both WPQT tests indicated good values of elongation and reduction of area and, in the cross-weld tensile tests the mode and position of failure was always ductile and in the parent pipe. See Table 8.12.

Review of welding procedure qualification test data for the Stittsville-Deux Rivieres project (see Table 8.13) indicates that at the test temperature of -5ºC a high level of toughness was obtained in the weld deposit comprising the K-Nova and Thyssen NiMo-80 with all values exceeding 130 Joules. If Charpy tests were performed at a lower test temperature, no data has been supplied so performance of this weld metal combination in more extreme (e.g. arctic) service cannot be assessed. However, given the good toughness at the -5ºC test temperature it seems worth investigating lower temperature toughness for future applications. The HAZ Charpy toughness is generally even better but occasional lower Charpy energy

Table 8.12
Stittsville WPQT Tensile Results on SAWL and SAWH Mainline Girth Welds and SAWL Backwelds [64]

Weld/Pipe	Test	YS / 0.2% MPa	TS MPa	Elong %	R of A %	Notes
Main line tandem welding on X100 14.3 mm w.t. SAWL pipe	All weld tensile	906 846	954 882	23 24	70 70	
	Cross weld tensile ASTM A370	725 726	765 797			Ductile fracture in pipe Ductile fracture in pipe
	Cross weld tensile CSA Z662		799 806 821 806			Ductile fracture in pipe Ductile fracture in pipe Ductile fracture in pipe Ductile fracture in pipe
Main line tandem welding on X100 12.7 mm w.t. SAWH pipe	All weld tensile	734 899	887 946	24 23	65 68	
	Cross weld tensile ASTM A370	825 788	847 866			Ductile fracture in pipe Ductile fracture in pipe
	Cross weld tensile CSA Z662		869 866 870 868			Ductile fracture in pipe Ductile fracture in pipe Ductile fracture in pipe Ductile fracture in pipe
Backwelding on X100 14.3 mm w.t. SAWL pipe	All weld tensile	N/A	N/A	N/A	N/A	
	Cross weld tensile ASTM A370	714 726	803 795	24 30	N/A N/A	Ductile fracture in pipe Ductile fracture in pipe
	Cross weld tensile CSA Z662		820 836 811 832			Ductile fracture in pipe Ductile fracture in pipe Ductile fracture in pipe Ductile fracture in pipe

Table 8.13
WPQT Charpy Test Results on X100 Line Pipe Girth Welds Stittsville-Deux Rivieres Project [64]

Weld/Pipe	Position	Charpy Energy J @ -5ºC	Charpy Energy J @ -5ºC Average	Shear %
Main line tandem welding on X100 14.3 mm w.t. SAWL pipe	Weld Centre Line	187 238 232	220	100 100 100
	HAZ	241 138 157	179	100 90 80
Main line tandem welding on X100 12.7 mm w.t. SAWH pipe (1)	Weld Centre Line	134 132 142	136	100 100 100
	HAZ	170 215 191	192	100 100 100
Main line tandem welding on X100 12.7 mm w.t. SAWH pipe (2)	Weld Centre Line	149 141 141	144	100 100 100
	HAZ	220 224 214	220	100 100 100
Backwelding on X100 14.3 mm w.t. SAWL pipe	Weld Centre Line	188 167 165	173	100 100 100
	HAZ	228 123 225	192	100 100 100

The values indicate a significant results spread that might be attributed to either marginal sampling position variation or proximity to the impact transition temperature. Again, to aid future applications, a fundamental study of HAZ microstructure, sampling position and Charpy energy would be worthwhile.

Other results of the welding procedure qualification tests indicated that the welds had performed well with good results in bend and nick break tests. No information on CTOD tests was provided. This project provided a further site-based experience of welding X100 and of extending variants of welding processes.

Finally, the WPQT tests provided a useful demonstration of hardness in the X100 girth welds and associated HAZs as shown in Table 8.14. The results in this table should perhaps be treated with some caution as the hardness points were generated to a prescribed pattern specifically for welding procedure qualification testing and, given that the exact location of fusion line and HAZ boundaries may vary between individual samples, it is possible that like for like is not being compared based simply on a geometric pattern. However, the SAWH (helical) pipe parent metal seems to be consistently harder than that of the SAWL X100; this observation being maintained both near the OD of the pipe (cap) and the ID (root) traverses. The cap weld metal hardness shows reasonable uniformity (as might be expected due to the lower level of parent/weld metal dilution at the cap) but a higher level of hardening appears to have occurred in the back-weld metal. The root HAZ of the helical welded pipe is consistently harder than the root HAZ in the SAWL pipe and, since this is consistent with the higher parent metal hardness of the SAWH pipe, suggests that a composition effect might be responsible. (No details of the SAWH pipe were provided). Finally the root weld metal hardness values are of an entirely acceptable level being below 300HV10 except for one, which at 325 HV10 appears to be inconsistent with others values in the same narrow region. The overall conclusion however, is that measured hardness values fall comfortably within the proposed 350 HV10 upper limit that is proposed for girth welds in X100 pipe.

Table 8.14
Hardness Traverse Results on X100 Girth Weld Procedure Qualification Tests
Stittsville - Deux Rivieres Project [64]

Position	Spacing	SAWL Mainline		SAWH Mainline (1)		SAWH Mainline (2)		SAWL Backweld	
		Cap	Root	Cap	Root	Cap	Root	Cap	Root
Pipe		275	292	330	292	301	290	263	272
HAZ	0.5 mm	250	252	344	312	322	311	244	249
HAZ		274	281	342	327	331	310	279	280
Weld	Equal	283	259	284	265	266	281	305	325
Weld		276	240	279	302	264	273	307	248
Weld		277	244	278	269	266	277	315	253
Weld		281	-	282	-	264	-	315	-
HAZ	0.5 mm	272	264	344	333	332	319	295	285
HAZ		271	241	343	324	327	308	268	254
Pipe		278	285	318	313	307	305	208*	290

* Hardness reading considered suspect.

8.1.2 Overall Conclusions from TransCanada Experience with X100 and X120 Line Pipe

a) TransCanada Pipelines Ltd (TCPL) are leaders in the practical pipe-lay of X100 line and have developed detailed understanding and experience with X100 beginning with fundamental studies in the mid 1990's. Through their joint sponsorship (with BP and selected pipe-welding contractors) of X100 welding studies at Cranfield University (UK) a firm foundation was established for the welding parameters, essential variables, parameter tolerances and welding consumables for the field welding procedures that followed.
b) Although TCPL have had experience with X100 line pipe from several different pipe mills in the Cranfield and other studies, it is apparent that a close working relationship was established with one supplier, JFE Corporation of Japan (formerly NKK and Kawasaki Steel of Japan). The manufacturer of the X100 is assumed to centre on the former NKK who supplied the material for Westpath Project in 2002. Although chemical composition details have not been supplied for all the pipe-lay projects, such details that have been made available suggest that a high degree of standardization and close control of chemical composition has been achieved and that the X100 steel alloy is based firstly on the relatively wide.
c) compositional allowances of CSA Standard Z245.1-02 but supplemented by TCPL's own in-house specification which places stringent limits on composition, particularly carbon content with a maximum of 0.07%. TCPL recently advised this PRCI project that X100 material from two further suppliers has now been installed and that the product of another pipe mill is currently under evaluation.
d) For recent projects TCPL has also taken delivery of SAWH X100 pipe from IPSCO (now Evraz Inc NA)- Regina Works. The IPSCO X100 pipe was of marginally thinner wall than most pipe from JFE and no details of chemical composition have been made available and fewer details of mechanical properties have been divulged than for the JFE steel. However, from the limited detail available it clear that TCPL's contractors successfully qualified

welding procedures for the IPSCO pipe for the Stittsville-Deux Rivieres Project. One observation from welding procedure qualification test results suggests that the hardness of the IPSCO SAWH pipe is harder by at least 20HV than its JFE SAWL counterpart. [64]

e) Care must be exercised if comparing the TCPL X100 material with other X100, particularly in respect of quoted Carbon Equivalent values since the TCPL CE is base on the formula used in CSAZ245.1-02 which differ from both the CE_{IIW} formula and the Ito-Bessyo Formula for CE_{Pcm}. The CSA formula usually gives a CE value lower than the IIW formula but higher than the Pcm. Hence the limit of CE $\leq$ 0.35 used by TCPL is equivalent to 0.45 - 0.46 (depending on the alloy balance) when using the IIW formula. However, the levels of preheat specified in TCPL and contractor's welding procedures (typically 100°C minimum) is similar to that specified by others for welding X100.
f) Main line welding utilizes GMAW root pass deposited with an internal welder. For all root passes TCPL standardized on Thyssen TS-K-Nova wire which appears to be satisfactory despite being (technically) marginally low on strength. Subsequent hot, fill and cap passes have been deposited with either single wire P-GMAW or single tandem P-GMAW using Oerlikon NiMo-1 although for Stittsville-Deux Rivieres and later projects, the wire was changed to Oerlikon NiMo-80 with apparently satisfactory results.
g) Tie-in and repair welding procedures have also been qualified successfully with both GMAW/FCAW and SMAW techniques, both of which appear to have been used. For the GMAW roots on tie-in welding Thyssen TS-6 K-Nova appears again to have been used successfully coupled with fill and cap passes with ESAB Tubrod 15.09 which has been used successfully by others. Use of cellulosic-coated SMAW electrodes for root passes in tie-in welds is viewed with caution at the X100 strength level, given the possibility of hydrogen embrittlement persisting in the root of the weld.
h) Details of tensile tests supplied by TCPL (along with details supplied by others) suggest that care and a standardized procedure must be adopted for measuring the all-weld metal strength of the narrow gap GMAW weld deposits. This fact was highlighted by earlier Cranfield work and is borne out by some apparent variability in all-weld metal tensile results. Review of the TCPL welding procedure qualification test results indicates that weld-metal yield-strength overmatching of the parent pipe in the longitudinal direction can be achieved with relative ease, thus assisting some strain-based designs, but that over-matching in the transverse direction cannot be taken for granted and in some cases, e.g. in a higher yield parent pipe, the weld metal may not over-match the parent pipe at all.
i) Unfortunately, no CTOD values were provided although some typical CTOD values can be obtained from Cranfield University references on development welding procedures on which later TCPL/contractor procedures were based.
j) No details were made available of the X120 developments at Godin Lake and it is understood that confidentiality agreements with ExxonMobil preclude further disclosure.
k) The Westpath project provided an early indication of application of X100 and its field welding and pipe-lay performance. The trial went well and the field welds contained only a few defects. It was a practical demonstration of feasibility but did not purport to simulate arctic pipe-lay nor does the service experienced by the X100 pipe in operation stress the pipe to a high design factor.
l) The Godin Lake project was a far more demanding demonstration of X100 pipe-lay in Canadian winter conditions and more closely simulated arctic pipe-lay. In addition to mainline welding operations, field bending and other pipe-lay operations were carried out successfully. The design factor experienced by the X100 line pipe in this development was

not declared but it is assumed that it is probably operating at a relatively low design factor. X120 was also laid at Godin Lake.

m) Stittsville-Deux Rivieres in 2006 provided further experience of practical pipe-lay in X100 and of use of helical (SAWH) welded line pipe in addition to the SAWL pipe used hitherto. The project also increased the X100 experience of contractor Louisbourg Pipelines, supported by CRC-Evans whose equipment was used. This was a summer time pipe-lay and therefore cannot be considered as a simulation of arctic conditions. The design factor under which the X100 pipe operate was not declared for the PRCI study.

n) Information supplied by TCPL on the above projects indicates that mainline field welds can be made by mechanized GMAW-P techniques with low repair rates and, where minor defects occurred on the Westpath pipe-lay they were mainly between the hot and first fill pass and in most instances were small enough to be acceptable to code requirements without repair. Refinement of the welding technique resolved the problem so no defects occurred between hot and first fill pass on the later Godin Lake project.

o) Although welding procedures have been successfully qualified and some technical details of process, procedures, process variables and consumables have been declared, the welding of X100 remains a precision operation requiring a greater experience than for welding some lower grades of line pipe. Variables such as tolerances of weld bevel dimensions and fit-up are more critical than for lower grades. Since the mainline welding procedures are based on GMAW-P, selection of the optimized pulse-programme and waveform is a pre-requisite. This depends on an experienced and informed contractor (and possibly client) and such experience is not easily gained. TCPL and their contractors appear to have the required degree of experience.

8.2 BP Full Scale Operational Trial - Spadeadam

8.2.1 General

In 2006 BP embarked on an X100 Operational Trial utilizing 0.5 km of 1219 mm (48 in.) diameter x 19.8 mm wall thickness X100 line pipe supplied by Sumitomo Metal Industries Ltd. [35] This long term trial at Advantica Technologies' site at Spadeadam, Cumbria, UK was undertaken to advance industry acceptance of the use of X100 on onshore gas pipelines and to demonstrate the long term operational performance of the pipe under normal and adverse conditions and at higher design factors. The X100 pipeline which is buried and pressurized with water at up to 180 barg (design factor of 0.8) is coated with a single layer fusion bonded epoxy coating (FBE) and is protected by a CP system. Construction was by conventional cross- country pipeline welding techniques and the test string has been subjected to a pressure cycling regime to simulate approximately 40 years of pressure service in two years. [35, 84, 85]

The pipeline was split into two sections A and B in which section B included various types of deliberate pipeline damage to demonstrate the application of defect assessment practice to X100. The simulated defects include potential construction incidents, potential operational deterioration and third party damage. [35, 84, 85, 86]

The trial pipeline also incorporated a number of X100 cold-formed field bends, X80 induction bends and an equal diameter X65 forged tee. [35, 85] Of the full 800 meters of the test pipeline, some 0.4 km of the X100 test pipe was from Sumitomo Kashima works and 0.4 km was supplied by Europipe from plate rolled by Mannesmann and Dillinger. The X100 material was purchased to a BP supplementary specification based on API 5L X100 / ISO 3183 L 690M and with Charpy impact testing allowing for a design temperature of minus 20ºC. [87]

The philosophy of the operational trial and of the pipe specification has been reported [35] and, in addition to the usual stress-based design requirements, maintenance of safety and integrity under strain based loading conditions were specified. Two failure modes were considered; failure of girth welds under tensile load and failure of the pipe by local buckling under compressive load and data from earlier full scale bending trials and curved wide-plate test data were utilized.

8.2.2 Line Pipe

8.2.2.1 Specification

Strength overmatching of the base metal by the weld metal remains an important consideration for girth welds to ensure integrity of girth welds containing flaws and under high tensile strain. This remains a challenge due to strength limitations with some current welding consumables and necessitates an upper limit for yield strength to be specified in the parent pipe. There is considerable strength anisotropy in X100 pipe which for UOE pipe results in strength overmatching in the longitudinal direction being easier to achieve than in the transverse direction.

Traditionally, line pipe strength has been specified on the basis of bare (uncoated) properties but some external coating processes such as FBE can result in increase of tensile properties and change of stress strain behaviour. [88] For higher strength steels, increase in the pipe yield strength after coating poses an additional challenge when overmatching by the girth weld metal has to be guaranteed and this must be factored in when specifying the line pipe.

Other factors to consider when specifying X100 pipe are the stress-strain behaviour of the pipe, the tensile strain capacity particularly in the longitudinal direction, and avoiding strain localization (as service strain is predominantly in the longitudinal direction. Maximum yield to tensile ratio and minimum uniform elongation needs to be specified.

The pipeline may also be required to resist local buckling under compressive load which can occur under conditions of foundation movement or seismic events. The compressive strain capacity can be affected by factors such as axial load, operating pressure, D/t ratio, stress-strain curve shape, anisotropy and stress discontinuities such as at welds and defects and geometric imperfections such as hi-lo or ovality.

Pipe should be tested using the Charpy and Drop Weight Tear Test to assess its fracture characteristics, particularly in respect of ductile fracture initiation and propagation control. Where larger diameter high strength e.g. X100 pipe is to be use for high pressure gas transmission, extremely high Charpy impact toughness is necessary to arrest a running fracture so the aim should be sufficient toughness to resist initiation and ensuring ductile behaviour coupled with the use of mechanical crack arrestors if pipe body toughness alone is insufficient to arrest running fracture.

A typical specification for mechanical properties in uncoated pipe is shown in Table 8.15.

Table 8.15
Specified Mechanical Properties for Welded X100 Pipe [35]

Parameter	Unit	Value
BM transverse yield stress	MPa	690-810
BM transverse tensile strength	MPa	758-896
BM transverse yield/tensile ratio	-	0.95 max
BM longitudinal yield stress	MPa	630-790
BM longitudinal tensile strength	MPa	758-896
BM longitudinal yield/tensile ratio	-	0.92 max
BM longitudinal uniform elongation (UEL)	%	3.5 min
BM Charpy impact energy at -20ºC	J	200 min
BM DWTT shear area at - 20ºC	%	85 min
BM Seam weld hardness	HV10	300 max

8.2.2.2 Base Metal Design

The microstructure of X100 base metal includes lower temperature transformation products such as lower bainite with a small amount of martensite-austenite (MA) to provide higher strength and adequate fracture toughness. This is different from say the typical X80 microstructure of upper bainite with fine ferrite.

The X100 mechanical properties must be obtained using a lean composition to maintain weldability and fracture toughness at lower temperatures, particularly after welding. In the case of the BP operational trial the optimized composition was a low carbon Mn-Cu-Ni-Mo Nb-Ti chemistry. This also maximizes austenite hardenability, maintains a low Pcm value (for good weldability) and limits alloying cost.

Published results [35] describe the composition of this X100 as shown in the following Table 8.16.

Table 8.16
Typical Composition of X100

C	Si	Mn	P	S	Others	N	CE	Pcm
0.06	0.10	1.85	<0.010	<0.001	Cu, Ni, Mo, Nb, Ti	<0.0040	0.48	0.20

Line Pipe Tensile Properties

The following Tables 8.17 – 8.20 summarize the tensile test results obtained from this modern X100 steel and analysis of the tensile testing appears in the published paper. The results underline the significance of specimen type to the measurement of transverse specimen properties. The strip specimens exhibit lower values of yield strength which is attributed to the Bauschinger effect which is more pronounced with high strength steel. This implies that care must be taken in selecting the tensile method to be used for transverse strength measurement and interpretation of results in the knowledge of the method used. There is no significant difference in the longitudinal properties measured by the two methods indicating that the absence of strip flattening in the API method implies that either method could be used for measuring longitudinal properties.

Table 8.17
Transverse tensile test results (8.9 mm round bar)

	$Rp_{0.2}$ MPa	$RT_{0.5}$ MPa	Rm MPa	$YS_{0.2}$ /TS %	El %	UEl %
Mean	776	779	837	92.8	19.4	6.2
Target	690/810	-	758/896	≤ 95.0	≥ 14.0	≥3.5

Table 8.18
Transverse tensile test results (API Strip)

	$Rp_{0.2}$ MPa	$RT_{0.5}$ MPa	Rm MPa	$YS_{0.2}$ /TS %	El %	UEl %
Mean	710	712	840	84.6	31.5	5.9
Target	na	na	na	na	na	na

Table 8.19
Longitudinal tensile test results (12.7 mm round bar)

	$Rp_{0.2}$ MPa	$RT_{0.5}$ MPa	Rm MPa	$YS_{0.2}$ /TS %	El %	UEl %
Mean	671	668	811	82.7	21.7	5.8
Target	na	na	na	na	na	na

Table 8.20
Longitudinal tensile test results (API Strip)

	$Rp_{0.2}$ MPa	$RT_{0.5}$ MPa	Rm MPa	$YS_{0.2}$ /TS %	El %	UEl %
Mean	657	637	811	81.0	34.1	5.4
Target	630/790	-	758/896	≤92.0	≥14.0	≥3.5

The mean yield strength in the transverse direction is around 120 MPa higher than that in the longitudinal direction and is attributed to the normal longitudinal and transverse anisotropy occurring in the plate which is augmented by work hardening during mechanical expansion, the effect of which increases with tensile strength and is more pronounced in high strength steels [35]. This also affects the YS/TS ratio which is around 81% in the longitudinal direction compared with around 93% in the transverse.

A relatively recent observation is that of pipe strength enhancement after fusion bonded epoxy (FBE) coating. In this process, typically the pipe is induction heated to a temperature of about 230ºC, at which point the coating is applied, followed by a holding at 200ºC for 200 seconds and then water quenched to 100ºC. Tables 8.21 and 8.22 indicate the increase of yield and tensile strength which is attributed to a form of strain ageing. This raises the question if mechanical design of the pipeline should be based on the ex-mill tensile properties of the pipe (conservative design) or if the higher properties obtained after coating might be considered. Further analysis of the effect of the coating treatment on tensile properties and the stress-strain curve is given in published paper [35].

Table 8.21
X100 Transverse tensile properties (round bar specimens/coated and uncoated pipe)

	$Rp_{0.2}$ MPa	$RT_{0.5}$ MPa	Rm MPa	$YS_{0.2}$ /TS %	El %	UEl %
Uncoated	752	751	804	94	21	5.4
Coated	804	805	836	96	20	5.2
% Change	6.9	7.2	4.0	2.6	-4.8	-3.7

Table 8.22
X100 Longitudinal tensile properties (API strip specimens/coated and uncoated pipe)

	$Rp_{0.2}$ MPa	$RT_{0.5}$ MPa	Rm MPa	$YS_{0.2}$ /TS %	El %	UEl %
Uncoated	661	655	788	84	36	5.9
Coated	737	736	821	90	37	5.4
% Change	11.5	12.4	4.2	7.3	2.8	-8.5

8.2.2.3 Line Pipe Toughness Properties

The following Tables 8.23 and 8.24 indicate the toughness obtainable from modern X100 line pipe [35] when measured by Charpy V-Notch testing and full wall pressed drop weight tear testing (DWTT).

The published paper indicates that transition starts at temperatures below -30ºC and that transition temperatures for 50% of upper shelf energy was lower than -80ºC for the base metal, -68ºC for the weld metal and -62ºC for the HAZ. This indicates a high level of toughness maintained down to low temperatures for each material or zone but probably insufficient to guarantee arrest of a running ductile fracture in a large diameter high pressure gas pipeline, thus indicating a need for separate crack arrestors.

Table 8.23
Charpy Toughness of X100 Line Pipe

	Base metal, J	Seam weld metal, J	Visible HAZ, J
Test Temperature	- 20ºC	- 30ºC	-30º
Min Value	181	117	57
Max Value	311	170	218
Mean Value	232	147	144
Target Value	200	≥100 ave/75 min	n/a

The DWTT results shown in Table 8.24 show satisfactory performance and a report of a DWTT transition curve indicated that a 85% shear transition temperature of -44ºC.

Table 8.24
DWTT Test Results on X100

	DWTT Shear Area (%)
Test Temperature	-20ºC
Minimum	88
Maximum	100
Mean	98
Target	≥85

8.2.2.4 Hardness of X100 Pipe

Table 8.25 shows typical hardness values in parent metal, weld and HAZ across the SAW seam of an X100 pipe. A feature of much X100 SAWL pipe is that of an extensive HAZ exhibiting a softening of typically 30 HV. This is a result of the lean composition parent material which resists hardening on welding and the slow, high heat-input multi-wire thermal cycle associated with the SAW seam welding of the pipe in the mill.

Table 8.25
Hardness Distribution of X100 Pipe

	Base Metal (HV10 average)	Weld Metal (HV10 average)	HAZ (HV10 average)
External Seam Weld	242	249	217
Mid Thickness	243	273	239
Internal Seam Weld	263	264	245
Target	≤ 300	≤ 300	≤ 300

Care should be taken with the interpretation of the above averaged hardness results for weld metal and HAZ as individual peak values may approach 300 HV10 in the weld. Also, such results should not be taken as indicative of the hardness levels that may occur in field girth welding of the pipes where much lower heat-input GMAW-P or FCAW-G processes are more likely to be used than SAW and where welding wire compositions may be less alloyed than the SAW wires used in the pipe mill. Therefore, hardness testing of the field welding WPQT's should be carried out thoroughly and should include the interface between girth welds and parent pipe and particularly the intersection between girth welds and seam welds where a higher alloy dilution is likely.

8.2.3 Girth welding of pipes

Specifications and Standards for Welding

The starting point was an established pipe welding standard e.g. API 1104 20th Edition - Welding of Pipelines and Related Facilities Nov 2005. Alternatively, ISO 13847 Petroleum and Natural Gas Industries - Pipeline Transportation Systems - Welding of Pipelines could have been used but supplemented with a different project specification. For pipelines, most operators will supplement the national, international or industry standard with a company specification or project specific specification. BP use internal documents; "Guidance on Industry Standard API 1104 for Pipeline Welding" and a "Guidance on Practice for Welding Consumable Control". The project drew on specifications for the X100 pipeline operational trial related to line pipe, bends and fittings welding written in 2006.

8.2.3.1 Planning and Qualifying Welding Procedures

The selected welding contractor performed a series of welding procedure qualification tests (WPQTs) on project material at their home base and also carried out visual and X-Ray inspections [87]. Mechanical testing of the qualification welds was conducted by an independent test house [89].

8.2.3.2 Range of Girth Welding Processes and Procedures

A comprehensive range of welding procedures listed below was qualified for the operational trial and were representative of procedures to be used on a full pipe-lay operation [89].

- Main line welding — Auto GMAW - P tandem
- Thru thickness repair — Manual STT® and FCAW-G
- Mid thickness repair to main line — Manual FCAW-G
- Cap repair to main line — Manual FCAW-G
- Prefabrication procedure — Manual STT® + Mech FCAW-G
- TTR for prefabrication — Manual STT® + FCAW-G
- MTR for prefabrication — Manual FCAW-G
- Cap-repair for prefabrication — Manual FCAW-G
- Back weld repair for prefabrication — Manual FCAW-G
- Back weld repair for prefabrication — Manual STT®
- Tie-in procedure — Manual STT® + Mech FCAW-G
- Thru thickness repair to tie-in — Manual STT® + FCAW-G
- Mid thickness repair to tie-in — Manual FCAW-G
- Cap-repair to tie-in — Manual FCAW-G
- Back-weld for tie-in — Manual FCAW-G
- Back weld for tie-in — Manual STT®

Welding Procedure Specification (WPS) for Main line Welding.

- 1219 mm (48 in.) OD x 19.8 mm w.t X100 pipe from Europipe (Dillinger/Mannesmann plate) and SMI Kashima
- Root pass GMAW-P single torch - Saturnax System 5
- Other passes GMAW-P tandem - Saturnax System 5
- Power sources Tandem Fronius TPS 4000
- ESAB Autrod 13.25 (1% Ni wire), Class ER 100 S-G, 1.0 mm diameter
- Weld prep double J bevel - precisely machined
- 5G, downhill, weaved multi-pass
- Polarity DC+
- Internal line-up clamp with Cu backing - removed after hot pass
- Max time lapse root-hot pass 20 minutes
- Ar/CO2 shielding gas 82/18mixture, flow rate 30/40 litres/minute
- Preheat 100ºC min   Interpass 150ºC max
- Sidewall dwell time 40/400 ms
- Stick out auto regulation
- Arc energy ranging from 0.16 - 0.60 kJ/mm (master) 0.14-0.58 (slave) - varying according to pass.

WPS for Through Thickness Repair

- STT®/FCAW-G process
- Power sources:
    1. Lincoln STT® 2 Version I
    2. Miller FCAW-G XMT 350 with Miller suitcase wire feeding box (12 RC model)
- Min total repair length 50 mm at bottom of groove - max length 700 mm to reduce restraint stresses.
- STT® consumable Lincoln Pipeliner® 80S-G Class ER 80S-G
- FCAW-G consumable ESAB Tubrod 15.09 Class E111T1 - GMH4
- FCAW-G shielding gas Ar/CO_2 82/18 at 30-40 litres/min

- Time lapse root/hot 10 minutes maximum
- Preheat 100ºC min interpass 150ºC max
- Direction STT® downhill / FCAW-G uphill Position 5G
- Heat input STT® 0.4 -1.4 kJ/mm and FCAW-G 0.6 - 1.4 kJ/mm

WPS for Mid-Thickness Repair to Main Line Welds
WPS for Cap Repair to Main Line Welds

- Broadly similar to the FCAW-G part of the thru thickness repair WPQT

WPS for Prefabrication

- 1219 mm (48 in.) dia x 27.5 mm X80 (equivalent 1219 mm (48 in.) x 36.6 mm X65)
- Process GMAW STT® manual for root pass
  FCAW-G hot to cap passes
- STT® Root consumable - Lincoln Pipeliner® 80 (1.0 mm dia)
  FCAW-G hot, fill cap passes - ESAB Tubrod 15.09 (1.2 mm dia)
- Shielding Ar/CO2 82/18 25-30 l/min root and 30-40 l/min hot to cap
- Preheat 100ºC (150 deg C for cap)
- Interpass 150ºC max (200ºC for cap)
- Time lapse root/hot pass 10 minutes max
- Compound V bevel 20-30º each side with 3-5 mm root gap
- Heat input STT® 0.6 - 1.0 kJ/mm and FCAW 0.8 - 1.5 kJ/mm according to pass
- Position 5G from root to cap, 5G for root and 1GR for remaining passes
- Direction of welding STT® downhill/ FCAW uphill
- External clamp + bullet tacks as required (100ºC for tacking)
- No of welders 1 per bug/gun - 2 bugs/guns (one each side)

WPS for Tie-in Procedure. Manual STT® and Mechanised FCAW-G Saturnax

- Butt weld tie-in 1219 mm (48 in.) x 27.5 mm X80 to 1219 mm (48 in.) x 19.8 mm X100
- Sumitomo X100 pipe to X80 Mannesmann
- Process GMAW STT®2 Manual root pass
- FCAW-G automatic for hot to cap passes - Fronius power sources
- Welding consumables - Root pass 1.0 mm dia Pipeliner® 80S-G.
- Welding consumable - Hot, fill and cap passes ESAB Tubrod 15.09 1.2 mm dia
- Shielding gas Root to cap Argon/CO2 82/18
- Position 5G Direction Downhill/Uphill
- Current DC +
- Welders 1 per bug/gun, 2 guns/bugs (one each side)
- External Clamp - Tack weld if necessary
- Time lapse between root and hot pass 15 mins max
- Preheat 100ºC min Interpass 150ºC max
- Flow rate 20-30 l/min root and 30-40 l/min hot, fill and cap
- Heat input STT® root 0.6 - 1.1 kJ/mm FCAW hot, fill, cap 0.8 - 1.3 kJ/mm

WPS for Through Thickness Repair to Tie-in. STT® Root/FCAW-G hot, fill and cap

- X80 or X100 (X100 Sumitomo only)
- Similar technique and conditions as the tie-in WPS
- Shielding gas flow rate 20-30 l/min
- Prep arc-air gouge plus brushing ad grinding
- Time lapse 10 minutes max
- Min repair length 50 mm. Max repair length 770 mm

WPS for Mid-Thickness Repair to Tie-in. FCAW-G hot, fill and cap

- Similar technique and conditions as the thru thickness repair to tie-in
- Shielding gas flow rate 20-30 l/min

- Prep arc-air gouge plus brushing and grinding
- Time lapse 10 minutes max
- Min repair length 50 mm Max repair length 1150 mm

WPS for Cap Repair to Tie-in. Manual FCAW-G technique

- Similar top cap run only of thru thickness repair to tie-in
- Min repair length 50 mm Max repair length 1150 mm

WPS for Back-Weld for Tie-in. Manual FCAW-G

- Internal single run repair to tie-in weld in X80/X100 using manual FCAW.
- Min repair length 50 mm Max repair length 1150 mm
- Heat input 0.7 - 1.0 kJ/mm
- Similar conditions to FCAW parameters of other tie-in procedures.

WPS for Back Weld for Tie-in. Manual STT®

- Internal single run repair to tie-in weld in X80/X100 using manual FCAW.
- Min repair length 50 mm Max repair length 1150 mm
- Heat input 04 - 0.7 kJ/mm
- X80 or X100 (X 100 Sumitomo only)
- Consumable Lincoln Pipeliner® 80 Class ER 80S-G
- Shielding gas Ar/CO2 82/18 Flow rate 20-30 l/min
- Preheat 100ºC min
- Current typically 120-150A, Voltage 19-21V, Travel 19-21 cm/min, WFS 4.0-4.5 in/min
- Heat input 0.4 - 0..7 kJ/mm
- Position 5G. Direction Downhill

8.2.3.3 Welding Procedure Qualification Tests

A total of 17 Welding Procedure Qualification Tests was used to qualify the above procedures and it was reported that only one WPQT was rejected (for defects by radiographic testing after 24 and 72 hours).

8.2.3.4 Standards and Required Values

8.2.3.4.1 Charpy Tests (to EN 875 / EN 10045-1)

The following Charpy energy values were required to be achieved in the welds for the operational trial

- Grade < X80 Ave 50 J, Min 40 J Temperature -30ºC
- Grade X80 Ave 60 J, Min 45 J Temperature -30ºC
- Grade > X80 Ave 80 J, Min 65J Temperature -30ºC
- Some Charpy tests were conducted at -20ºC, -40ºC, - 60ºC and -80ºC on weld metal capping, fusion line side capping and fusion line FL+2 mm side capping on both sides of the weld
- Ductile shear area shall exceed 50%

8.2.3.4.2 Macrosection and Hardness

350 HV10 max. (This contrasts with the conventional limit of 300 HV10 max for lower grade pipe welds).

8.2.3.4.3 Transverse Tensile

Weld metal yield strength 810 MPa minimum.
Actual failure stress may be lower if actual yield strength of parent metal is less than 810 MPa.

8.2.3.4.4 All Weld Tensile

Weld metal yield strength 810 MPa minimum (to ensure overmatching)

8.2.3.4.5 CTOD Test (to BS 7448-2)

CTOD Weld Metal @ - 20ºC
CTOD HAZ Side B @- 20ºC

8.2.4 WPQT Properties Achieved in X100.

BP performed extensive testing on the welding procedure qualification welds and most of the precise results remain proprietary at the time of writing. However, a summary of some important test results obtained from the GMAW main-line welds and some for tie-in repair welds made by manual STT® and FCAW techniques is given in the following paragraphs. The full results provided valuable information on the physical characteristics of X100 welds made using a small number of welding consumables and different X100 pipes. The choice of ESAB Autrod 13.25 (1% Ni wire), an AWS Class ER 100 S-G wire used at 1.0 mm diameter for main line welding is considered to be successful but wire composition for this application is probably not yet optimised and weld/parent metal dilution effects, if used with different X100 parent metals, would need to be investigated.

Tie-in welds, repair and re-repair welds, together with fabrication welds and grade transitions have been made successfully for the operational trial project using just two welding consumables either singly or in combination. The Lincoln Pipeliner® 80S-G (AWS Class ER 80S-G) GMAW wire is recommended by the manufacturer [90] for root pass welding of pipe up to X100 grade and for hot pass, fill and cap pass welding of pipe up to X80 grade. It was used for root passes of tie-in joints, back welding and repairs of tie-ins, prefabrication work and weld repairs. The bulk of the welding of those same joints was accomplished using a 1.2 mm diameter ESAB Tubrod 15.09. This is an AWS A5.29 rutile-cored wire with 2.3%Ni, 0.2 Mo, 0,2% Cr, 0,3% Cu and small additions of V and Nb.[91] This consumable is claimed to produce weld metal with a yield stress of typically 780 MPa, a tensile strength of 840 MPa, 19% elongation and 70 joules Charpy at -40ºC. The combination of all-weld mechanical properties and productivity of this gas shielded flux-cored arc weld for wider weld bevel joints such as tie-in and repair welds suggests that this wire is very suitable for X100. Tubrod 15.09 is an all-positional wire except for vertical-down welding and, in some batches, the nickel content may be considerably higher, up to 3%.

8.2.4.1 Tensile Tests - Main-line Welds

8.2.4.1.1 All Weld Tensile Tests - Main-line Welds

The narrow gap profile of the mechanised GMAW girth welds restricts the cross-sectional area available for all-weld tensile tests and material must be selected with care in order to sample weld material only while maximising the available cross sectional area. Table 8.26 summarises typical all-weld tensile results measured from prismatic test pieces and indicates that typical yield and tensile strengths of weld metal from Autrod 13.25 wire can comfortably exceed the longitudinal direction yield strength of X100 pipe but cannot be guaranteed to exceed the parent metal transverse strength in all cases. See Tables 3 and 4 and discussion in 8.2.4.1.2

Table 8.26
Typical all-weld tensile test results for GMAW main line welds
(with line pipe longitudinal properties for comparison)

Property	All-weld (ave) Prismatic	Parent Pipe Longitudinal
Yield Strength, $R_{p0.2}$ MPa	814	620 -780
Tensile Strength, R_m MPa	859	748 - 898
Yield to Tensile Ratio	0.95	0.74 - 0.91
Elongation%	16.5-20.5	26--43
Uniform Elongation%	5.5 - 7.5	2.0 -6.0

8.2.4.1.2 Overmatching of Main-line Girth Welds

Comparative analysis of all-weld metal yield and tensile strengths and those of parent pipes indicate that guaranteeing that the weld metal will overmatch the parent is dependent on multiple factors. For the purpose of illustration, weld strength matching levels described here are those taken at 0.5% total strain. Although the full data remains proprietary to BP it is apparent that;

i) the yield strength of a pipe is increased by typically 6 - 11% due to the thermal cycle associated with the FBE coating process.

ii) weld metal that just matches or barely overmatches the transverse yield strength of the uncoated pipe may under-match the same pipe after coating. Variation may be from 0 to - 2%.

iii) there is a statistical distribution of weld metal yield strength and the higher samples in the distribution may show a wide differential in overmatch between uncoated and coated pipe. e.g. 12% overmatch with uncoated pipe might drop to 5% on FBE coated pipe.

iv) there is a statistical distribution of yield strength between different X100 pipes from the same order and between X100 pipes from different suppliers. Thus, a weld metal that overmatches one X100 uncoated pipe by 12% may overmatch another by only 10%.

v) due consideration needs to be given to how representative the all-weld tensile test piece is of the weld itself. Prismatic test pieces, with dimensions carefully determined to sample weld metal only are likely to be more representative than round bar specimens which will be either of minute cross section or, if larger, will sample a combination of weld metal and HAZ.

vi) the transverse direction yield strength of the parent pipe is invariably higher than that in the longitudinal direction. This means that the weld metal yield strength will generally overmatch the pipe longitudinal yield strength by a greater margin and example average values of overmatch were 24% for uncoated and 11% on coated pipe. If weld metal yield strength meets the typical specified minimum of 810 MPa, its overmatch of the longitudinal yield strength should allow sufficient margin to resist local strain concentration at the weld.

vi) all of the above observations relate to GMAW weld metal produced from one proprietary welding wire and, although considered generic, could differ for welds deposited from other welding wires or made under other conditions.

8.2.4.1.3 Cross-Weld Tensile Testing Main-line Welds

The procedure qualification tests on GMAW mainline welds also yielded useful data in respect of cross weld tensile tests which are summarised as follows:

- Cross weld tensile strengths ranging widely from 789 - 856 MPa with an average of 834 MPa were obtained with the final tensile failure occurring always in the parent metal.
- Measured tensile strengths of parent pipes ranged from around 840 to 870 MPa.
- The cross weld tensile tests were tested with the weld reinforcement removed and, although the position of failure was always in the parent metal, it was noted that the pipes used for the qualification test were not the individual strongest of the batch (at 865 - 898 MPa tensile). This suggests that, in some instances, the observed overmatching of the tensile strength of the parent metal could be marginal and for strong pipes the situation may be reversed and could become a defect acceptance issue if overmatching is relied upon.

There may be scope for use or development of a welding wire guaranteeing a tensile strength weld deposit of around 900MPa, providing it is in combination with adequate elongation, low temperature Charpy toughness and CTOD values.

8.2.4.2 Charpy Toughness Tests on Main-line Welds

A summary of weld metal and fusion line Charpy energy values was obtained for mainline welds. Although full results remain proprietary to BP they allow the following conclusions to be drawn.

- The specified Charpy toughness at -30ºC was 65J minimum individual and 80J minimum average.
- The average value of weld metal was 113J, comfortably exceeding the 80J specified minimum average.
- The fusion-line impact energies showed considerable spread and seemed to be parent material -dependent. The "average" values from each set (material) ranged from around 90J up to 150J.

At the FL+2 mm sampling position, all Charpy values were high indicating little deleterious effect of the main line GMAW welding on the HAZ although the parent metal will clearly influence these results. Average values ranged from around 170J to 220J.

It may be concluded that the X100 parent metal performs favourably to mechanised GMAW welding retaining much of its initial toughness in the HAZ. Testing appeared to not deliberately sample the GCHAZ but typically some of this region was sampled in the fusion-line Charpy tests which exhibited a slightly lower toughness but, in conventional terms was of a satisfactory level. The weld metal toughness was also satisfactory in conventional terms but was typically half the level of unwelded parent metal. This suggests that for more extreme temperature applications, there may be a need for welding consumables to be developed to produce weld deposits with an even higher level of toughness.

8.2.4.3 CTOD Tests on Main-Line Welds

The mainline weld metal CTOD values at a test temperature of -20ºC range from 0.14 - 0.19 mm, which is consistent with general expectations for high strength narrow gap GMAW welds. The CTOD values for the HAZ were generally higher and with a wider spread but were significantly material dependent averaging 0.38 mm for the best results down to 0.19 mm for the least tough.

The CTOD values could be used in conjunction with pipeline design parameters in an engineering critical assessment to determine whether allowable defect dimensions are practical. It is noted that BP intend to conduct curved wide plate tests on girth welds from the operational trial to validate defect acceptance limits. These results along with others suggest that there may be a need for development of welding consumables and/or welding process improvements to produce weld deposits with improved CTOD and defect tolerance. The results also demonstrate the parent material dependence on HAZ CTOD performance.

8.2.4.4 Hardness Tests on Main-Line Welds

Table 8.27 summarises maximum and maximum average Vickers hardness data for mainline girth welds. (The maximum average is defined as the average of all maximum values from each macro-section).

Table 8.27
Maximum and Maximum Average Hardness
Tests for Mainline Girth Welds

Location	**Weld Metal Hardness HV10**	
	Maximum	Max Ave
Weld Cap	318	293
Mid Thickness	334	229
Weld Root	335	307

HAZ average maximum hardness values were again parent material dependent and ranged typically from 280 - 314 HV adjacent to the weld cap regions, typically around 260-270 HV at mid thickness and typically 270 - 280 HV in the root regions.

These results indicate that conventional 300 HV maximum limits, as specified in several pipeline codes, are unlikely to be achievable in these high strength main-line weld metals but that a maximum limit of 350 HV should be readily achievable. However, it should be noted that this HV limit is used as a proxy to indicate sensitivity to hydrogen assisted cold cracking, and this correlation may not be strictly true for the microstructure and stress levels realised in all X100 pipe and welds. The general level of the average HAZ hardness suggests that a marked hardness gradient may exist in some HAZs and that, in some instances, a small extent of HAZ softening may occur, even in conventional low heat input mechanised gas metal arc welding of X100 pipe. Most HAZ hardness values remain comfortably under the 350HV limit that has been specified for X100.

Tensile Tests - Tie-in and Repair Welds

8.2.4.4.1 All-weld metal tensile strength for tie-in, fabrication and repair welds

Since the full penetration and partial penetration repair welds were made using essentially the same processes and consumables and similar procedures to this for the tie-in and fabrication welds, the analysis of mechanical properties was combined.

Weld metal consisted of a mixture of the STT® Pipeliner® 80S-G root run and several runs of the FCAW-G weld produced from Tubrod 15.09, the latter being diluted to a greater or lesser extent by the adjacent parent metal.

Full details of resulting mechanical properties remain confidential to BP but may be summarised as follows.

- All-weld yield strength range of 738-812 MPa (average 773 MPa)
- All weld tensile strengths ranging from 775 to 845 MPa.
- Transverse direction weld strength overmatch ranging from 2 to 29% (average 17%) against pipes from one supplier and a range of an under match of 5% to an overmatch of 31% against pipes from a second supplier.
- The extent of weld metal overmatch against the longitudinal direction properties was in all cases satisfactory.

Results such as these underline the importance of limiting yield strength and tensile strength ranges for high strength pipe as tightly is possible.

8.2.4.4.2 Cross-weld tensile test results for tie-in, fabrication and repair welds

The cross-weld tensile properties from tests taken from repair and tie-in WPQT's indicated that a satisfactory level of girth weld strength can be maintained with most tensile failures occurring in parent pipe. Full results remain proprietary to BP but typical results [92] may be summarised as follows:

- Mainline repairs - tensile strength 760-840 MPa
- Tie-in welds - tensile strength 805- 830 MPa
- Tie-in repairs - tensile strength 700-725 MPa

8.2.4.5 Cross-weld Charpy Impact Energy Results for Tie-in, Fabrication and Repair Welds

Charpy impact testing was carried out at -30ºC with the same specified criteria of 65J minimum individual and 80 J minimum average values as for main line welding.

Full results remain confidential but it was observed that the lowest single result of the weld metals tests was 35 Joules, the corresponding average being only 68 Joules thus not meeting the specified values and indicates the need for further work to optimise welding consumables, gas mixtures and parameters for FCAW welding of tie-ins, fabrication welds and weld repairs.

A satisfactory level of Charpy impact values was achieved for:

- Weld fusion line with average values ranging from 83J- 146J
- Fusion Line + 2 mm zone with average values ranging from 190J - 210 J

Results of fusion line and FL + 2 mm were again parent material dependent, indicating the need for purchasers to understand the chemical composition end metallurgy of the X100 material they plan to use.

8.2.4.6 Weld Metal and Fusion Line CTOD Values for Tie-In, Fabrication and Repair Welds [92]

Fracture toughness testing carried out at -20ºC on B x 2B SENB centre weld test specimens from tie-in, and full and part-penetration repairs yielded CTOD value with delta-m or delta-c failure mode. The overall average value was 0.12 mm and little difference was observed between the results from different repairs. The CTOD value is probably representative of the bulk weld deposit primarily from the Tubrod 15.09 FCAW electrode, with minimal influence from the Pipeliner® 80S-G or from parent metal dilution with the test zone sampling the centre weld.

Further CTOD tests sampled the fusion line area of the same welds, several of which (tie-in, and full and part penetration repairs resulted in a higher level of CTOD than in the weld metal itself and with all failures being delta-m or delta c-type. Although full results remain confidential average summary results are as follows.

- Tie-in girth weld - average CTOD 0.40 mm
- Full penetration repair - average CTOD 0.32 mm
- Part penetration repair - average CTOD 0.29 mm

Results such as these indicate the toughness and potential defect tolerance of the parent metal after tie-in or repair welding.

8.2.4.7 Hardness of Tie-in and Repair Welds

In contrast to the higher peak hardness values experienced with the mainline GMAW welds, the maximum hardness of these STT®/FCAW repair weld metals only marginally exceeded 300 HV in the weld metal and were mainly well under 300HV in the X100 HAZ. This is probably attributable to a slower weld thermal cycle of the tie-in and repair techniques compared with that of the mainline GMAW welding.

8.2.5 Production Welding

Full details about the production welding remain confidential to BP [92] but the work was successfully completed in just over three weeks despite being carried out in very wet and cold UK winter conditions which provided a demanding test of durability and ruggedness of equipment and for the operating personnel.

The interface controllers, wire feed units, welding heads, bands and earth return clamp were housed inside purpose-built shacks for weather protection. The welding shacks had hinged floors that could be folded under the pipe and profiled end-flaps which fitted around the pipe to protect it against the elements during welding (a fairly standard arctic welding procedure).

The diesel generator, welding power supplies, air compressors, pre-heating gas bottles and shielding gas rack were accommodated on a separate trailer which was towed separately. Power cables and hoses were bundled into one umbilical.

Other aspects of the production welding and lessons learned include the essential variables of pipe composition (limits of +0.01 and -0.02 on P_{cm} value) and joint design, where tolerances of ±0.5º on bevel angle, ±25% on root face and +0.5mm on root gap would be considered restrictive on a large scale construction. The sensitivity of the mechanised GMAW process to wider limits of these parameters is a technology gap that merits investigation; otherwise in a larger scale contract larger numbers of procedures may need to be qualified or higher contract costs may be incurred.

Pipe misalignment remains an important issue in all mechanised GMAW welding since it impedes achieving fit-up within the required tolerances and root deposition. A pipe end diameter tolerance typically conforming to ISO 3183:2007 of ± 1.6 mm and out-of-roundness tolerance of 1% maximum is necessary. For mainline welds, a good internal clamp is needed to reduce the extent of misalignment but for pipe-to-fitting welds and tie-in welds where an external clamp is used and in instances where fittings cannot be rotated to optimise fit-up, the problem remains.

Misalignment is particularly important for strain based design conditions due to potential to severely reduce tensile strain capacity.

Some preheating for welding is inevitable with X100 pipe and a pre-requisite is that pre-heating should be controlled and uniform around the full circumference and that the specified pre-heating temperature be achieved and controlled. Traditional preheating with propane burners may not achieve the required uniformity and induction heating (as used routinely on offshore lay barges) is an alternative option. A maximum preheat and inter-pass temperature of 150ºC was specified for X100 with the possible intention of limiting any HAZ softening effects, but this may be considered restrictive and the 100-150ºC range would be difficult to maintain in a larger scale pipe lay. The sensitivity of the process to higher inter-pass temperatures may merit further investigation as sustained periods at high inter-pass temperature will retard cooling rates which may affect the strength of the completed welds.

During production welding a specified number of passes must be deposited before welding may be interrupted and the weld was allowed to cool below the minimum preheat temperature. [92] There may be scope to investigate if the minimum number of passes that are required before cooling might be allowed, particularly for mechanised GMAW-P which is a low hydrogen welding process.

The process used for mainline welds was mechanized GMAW-P in single torch mode for the root pass then tandem mode for cap and fill passes, the latter resulting in higher travel speeds and high deposition rates.

The two-wire tandem system increases both length and area of the weld pool thereby reducing the effective arc force for a given welding current and is less prone to producing lack of fusion defects as the joint sidewalls are exposed to the molten weld pool for a longer duration. It is also claimed that the shape and size of the weld pool may reduce the risk of solidification cracking and assist degasification thereby and reducing susceptibility to pore formation.

Tandem GMAW-P is complex, dependent on the control of a large number of parameters and has only become viable recently with improvements in power source technology and microprocessor control [92, 93] It uses a pulsed waveform (typically 50-220Hz) resulting in less spatter and better positional control than with conventional dip-transfer modes and is stable at lower mean currents which would normally result in unstable globular transfer with a standard DC power source.

The refinement and precision of the mechanized GMAW-P process and careful selection of welding consumables as applied by BP and by others for girth welding of X100 has produced excellent results and has allowed most specified properties to be achieved and, no doubt, with meticulous project planning and all the experience gained from X100 development work experienced operators and contractors should be able to apply the technology to larger scale developments. The same would probably not be true for operators and contractors lacking the same development history and preliminary experience. The impression is gained that the full effects of all process, procedure and materials variables are not known or understood by all operators or contractors.

It is interesting that BP and Serimax did not utilise the dual-tandem system known as CAPS and developed by the Welding Engineering Research Centre (WERC) at Cranfield University.

Although this system offers significant potential gains in productivity, it was considered at the time to be insufficiently proven for field use and probably unlikely to provide economic advantage in the relatively short run of pipe welding for the operational trial. [83] Although a field reliability trial of CAPS was carried out at Edmonton in 2003 in winter conditions, welding was on lower strength X80 material, so a proving trial utilising the CAPS system under site production conditions with X100 should be considered.

Tie-in welding cannot use the same form of mechanized GMAW-P as the pipes cannot be fitted to anywhere near the same degree of precision, misalignment is generally greater particularly where a pipe has been cut and the preparation is dependent on body tolerances and a larger angle weld bevel and hence wider weld preparation must be used. The flexibility required to complete the root pass can be provided by semi-automatic GMAW-P used with the STT® process and with appropriate high strength welding wire can be suitable for higher strength steels like X100. The traditional pipeline root deposition technique of vertical down welding using a cellulosic coated SMAW electrode is inapplicable for these higher strength steels and it is known that attempts to make welds incorporating cellulosic root runs followed by hot-pass fill and cap welding with consumables of lower hydrogen potential still results in susceptibility to fracture originating in a high hydrogen content root region. Gas-shielded vertical-up FCAW welding of tie-in hot, fill and cap passes with appropriate filler materials has been shown to produce high quality welds where the combination of strength, toughness and ductility come close to meeting the desired levels for X100 but there is scope for developing and investigating further consumables with the objective of improving selected properties and optimisation.

8.2.6 Overall Conclusions from the BP Operational Trial

The BP operational trial demonstrated the feasibility of X100 mainline welding for pipeline site construction under UK winter conditions using the Serimax GMAW girth welding system. Using a limited number of welding stations proved the viability of the technology although the limited number of joints to be welded was insufficient to obtain a true measure of the potential productivity of the Serimax system.

A total of 58 mainline tandem welds were made without a single repair. Welds were examined by X-radiography and automatic ultrasonic testing, followed by hydrostatic pressure testing then tested in the operational trial by pressure fatigue cycling to simulate a 40-year design life. On completion of the operational trial in 2009, further examination and testing of selected welds, including mechanical and curved wide-plate testing will be conducted to provide a searching and comprehensive evaluation.

Some minor defects such as lack of inter-run fusion between the root and hot passes were detected by auto-UT but such defects were within the acceptable limits of the specification.

It is noted that heating of the line pipe for application of anti-corrosion coating results in some thermal ageing and increase of the measured transverse yield strength of up to 70 MPa. Mill release test results are normally on uncoated pipe and would not account for this effect. This is unlikely to cause any problem with under-matching of the girth weld metal yield strength relative to the longitudinal yield strength of the pipe, but may result in under-matching relative to the transverse direction yield strength where the differential between weld and parent strengths is generally much lower. Further research of the effects of thermal ageing on X100 mechanical properties and weld-parent overmatching characteristics should be considered.

The extent by which metal yield strength over or under-matches X100 parent pipe yield strength in both longitudinal and transverse directions is worthy of further study on a wider range of line pipe batches (and from different manufacturers) and with a wider range of weld metals.

No effects of possible hydrogen embrittlement from cathodic over-protection have yet been assessed although low, medium and high levels were applied in the operational trial and post-trial testing may provide further understanding. Some small scale environmental cracking tests on X100 welds could be carried out.

Main-line weld metal Charpy impact energy values were generally satisfactory but some fusion line values were below the specified limit.

Main-line weld metal CTOD values were generally acceptable and were consistent with normal expectations for high strength narrow gap welds and it is recommended that engineering critical assessments be carried out for each pipeline developments using WPQT CTOD data and pipeline design parameters. This may point to a need for development of improved toughness weld metals at the X100 strength level.

Mainline weld hardness levels often exceed 300 HV10 and a limit of 350 HV10 should be set. This may require some changes to pipeline welding codes for X100 although fundamental work to determine the relationship between hardness and hydrogen cracking for X100 would be of benefit in determining the optimum specified limit. Occasional high HAZ hardness could be experienced but much of the HAZ remained around or below 300 HV. In some instances, there may be some HAZ softening.

For tie-in welding the combination of root welding by STT® single wire semi-automatic GMAW followed by welding the bulk of the joint using a FCAW-G process works well but it is suggested that the method of fit-up should allow for the use of low-hydrogen SMAW deposition of bullet tacks. The STT® process copes well with significant levels of misalignment.

The FCAW-G consumable used for tie-in and repairs provides an average all-weld metal yield strength of 773 MPa which is insufficient to guarantee an overmatching of all X100 line pipe yield strength, although longitudinal direction properties should generally be overmatched. The required Charpy impact energy values were not always met and CTOD values were modest. This points to an opportunity to develop improved FCAW wires to produce deposits at a slightly enhanced strength level in combination with higher Charpy toughness and CTOD.

BP's Operational Trial succeeded in testing the girth welds to a true design factor of 0.8 and as such represent a significant step towards full scale implementation of grade X100 line pipe.

8.2.7 Other Recommendations

- Determine the cause of low fusion line impact energy values in mainline single tandem welds in X100.
- Obtain curved wide plate test data from STT®/FCAW-G tie-in welds in X100.
- Refine root and hot-pass procedures to eliminate lack of inter-run fusion in single tandem welds.
- There is scope for further comparison of single wire, single tandem and dual torch mechanised welds on similar material.

- Optimise weld parameters and improve strength and fracture toughness of STT®/FCAW-G tie-in, fabrication and repair welds.
- Aim to widen tolerances on weld preparations, widen the range of shielding gas compositions and create an approved parameter envelope within which sound welds will be produced.
- There is a general need for development of improved welding consumables.
- Specify reduced ranges for min/max yield strength in X100 pipe to ease the weld-parent metal overmatch requirement.
- Qualify semi-automatic FCAW-G back-up procedures for tie-ins and fabrication welds.
- Investigate if welds can be interrupted and cooled safely after less than a minimum deposition of four passes to avoid hindering construction schedules, particularly for tie-in and fabrication operations.
- Specify options for remedial action when misalignment exceeds the specified 3 mm maximum limit.

9. Assessment of Contractor Capability in Context of X100 Welding Technology

9.1 Definition of First and Second Level Contractors

For the welding of high strength line pipe in pipeline construction a distinction should be made between the first level or managing contractor and the second level specialist contractors who are usually hired for their specific skills and expertise in defined field of operation. These may be described as follows.

The first level broadly-based managing or construction contractor usually takes on responsibility for a wide range of operations including negotiation and preparation of easements and rights of way, procurement of line pipe, bends, fittings, pumps, compressors and valves (although in some contracts such items will be procedure by the client or operator and free-issued to the contractor at site). This first level contractor may also take on responsibility for all movements, logistics, provisions, hire of equipment and most importantly hire of work force. Although project management, supervision and some work force may include permanent or long-term employees of the first level contractor or its subsidiaries, the nature of pipeline construction means that a large proportion of the site personnel may be hired on short-term contracts nationally or more frequently on a local basis. The first level managing contractor or pipe-lay contractor will provide or hire the heavy equipment and operating personnel. They will generally manage the total pipeline construction programme including operations such as pipe stringing, trenching, lowering and back fill, road, rail and river crossings, hydrostatic testing and ground reinstatement. Seldom will they directly manage the detailed field welding operations; this will more likely be sub-contracted to a specialist company i.e. the second level contractor.

The second level contractors undertake critical and important operations usually of a specialized technical nature including qualification of welding procedures and personnel, preparation of pipe end for welding, field-welding of the pipeline and shop welding of sub-assemblies, non-destructive testing of welds, field coating of weld joints and field repair of mill applied coatings and installation of cathodic protection systems. Such specialist contractors may also perform field cold-bending operations or provide equipment and train others to perform such tasks. On large pipeline projects, the second level specialist contractors may provide equipment and systems together with a core of skilled personnel who will train and supervise locally recruited labour of varying skill levels to use the equipment and perform the required tasks. In some cases a core of itinerant skilled labour may stay with a specialist contractor from job to job, providing a larger core of experienced personnel. This can happen in the case of welding personnel.

There has been a step change in the welding of pipelines over the last 20 years with an increasing tendency for mechanized and semi-mechanized girth welding systems to replace manual welding by shielded metal arc technique. Although the latter remains widely used for small scale pipeline developments and maintenance, particularly in the lower strength grade pipes, the use of techniques such as mechanized gas metal arc welding has become a pre-requisite for its economic and technical benefits with the advent of higher yield strength grades of line pipe. The benefits of such systems are further increased for long distance or transcontinental pipeline construction and recent innovations such as tandem arc and dual torch techniques can add further economic advantages in higher productivity. Furthermore, the precise control of welding parameters such as heat input, bead placement and weld pool control and the use of narrow gap weld preparations have become essential to optimize weld metal microstructure and mechanical properties, particularly the all-important balance of strength and toughness which is essential for materials like X100.

Implementation of these advanced techniques as described above is very much the preserve of specialized contractors who have developed and qualified welding procedures and techniques by themselves or in co-operation with client-operator companies, research facilities or other technical institutions. The ability to manage and implement such technology is unlikely to be found without a core of specialist companies, referred to here as second level contractors.

9.2 First Level Contractors - Experience and Capability

It has proved almost impossible to elicit information from first line (managing) pipeline contractors on their detailed experience of working with X100 line pipe. This is probably due to the fact that X100 (and X120) have not yet been used on a major pipeline; only for trial inserts on expansions of existing pipelines. A survey of pipeline contractors listed on the websites of the American Pipeline Contractors and Pipeline Industries Guild (UK) revealed no information about pipeline welding capability for any grade of line pipe. Although some of the contractors show examples of trenching, pipe-stringing and pipe-lay operations, there is no indication of in-house welding capability of either the traditional or modern variety. In the absence of such information it must be assumed that the welding expertise and facilities are bought in from secondary specialist contractors and this carries the implication that, where a contract to build an X100 or X120 pipeline is awarded, it is incumbent on the operator purchaser to specify welding requirements in detail and to prequalify and monitor any secondary sub-contractor who will provide this service.

9.3 Second Level Contractors - Experience and Capability

Existing experience and enquiries to operators and specialist contractors in the pipeline industry suggests that detailed expertise and experience resides with a very small number of pipe-lay welding contractors, with technical specialists in oil and gas companies and with research and technical institutions involved with development work. **[94]** The manufacturers of high strength steel pipe have some knowledge of the weldability of X100, particularly in regard to longitudinal or helical seam welding which they must perform in the mill but it is a moot point whether any other welding development work they may have done in technical support of their product is simulative of field pipeline girth welding or not.

Companies with genuine experience of development and practice of field girth welding procedures include

- CRC-Evans (Houston, USA)
- Serimax - formerly Serimer-Dasa (Mitry-Mory, France and Houston, USA)
- RMS Welding Systems (subsidiary of O.J. Pipelines, Nisku, Alberta, Canada)
- Marine Construction Ltd. Canada
- Louisbourg Pipelines Canada
- Saipem - Reference to PASSO (Mechanized GMAW welding for an ENI/CSM TAP Project)

It is not known for certain if Saipem (Italy) have made field welds in X100 but as CSM have conducted several fracture control (full-scale burst tests) at their site in Perdas Defogu, Sardinia, the test-strings have had to be girth welded but further details are not currently available.

The experience of CRC-Evans and Serimax is greater, extends back for a decade and results from their early collaboration with the Welding Engineering Research Centre of Cranfield University, UK where fundamental research work led to the development of mechanized GMAW girth welding processes for X100. Much of the Cranfield work has been published [51, 95, 96] and demonstrates that many tests had to be carried out to select welding consumables and optimize welding details and parameters to achieve welds with the requisite mechanical properties. The work also demonstrated the need for precise control of welding variables, involving a degree of precision not required for welds in lower strength line pipe with, perhaps the exception of X80. This suggests that pipeline welding contractors having a history of welding X80 may need a shorter development period for welding X100, than those who have not.

The experience of CRC-Evans, Marine Construction Ltd and Louisbourg Pipelines in the field-welding of the X100 and/or X120 inserts to TransCanada Westpath and Stittsville projects is proof that the procedures developed worked in the field. In each case CRC-Evans welding equipment was used and some amount of technology transfer probably contributed to the success. The experience of Serimax in welding the test string for the recent operational trial by BP in Spadeadam [85] is further evidence of the laboratory qualified welding procedures being employed successfully in the field, albeit on a limited number of welds and possibly a generous timescale not simulative of genuine pipeline lay rates.

RMS Welding Systems co-operated with TransCanada Pipelines Ltd and Cranfield University in development of girth welding procedures for X100 and with a successful joint TCPL/BP simulated winter field trial of equipment, albeit not on X100 pipe.

In the case of X120, a limited number of publications and brief knowledge of the TCPL-ExxonMobil Field trial at Godin Lake provide an example of field weldability of X120. However, information on this product has not been widely disseminated and it is understood that most experience resides jointly with ExxonMobil and steel makers who developed and promoted the product and with CRC-Evans for development of field welding. It is unknown if others in the industry are competent in the techniques for welding and deploying the X120 product.

Further development work will has been done in the research and development laboratories of the leading welding consumable manufacturers, in pursuit of improved welding consumables particularly for GMAW, metal-cored arc welding and possibly flux-cored arc welding. However, it is difficult to assess how much of this has translated into field use at the present time.

The records of X100 welding development work under the sponsorship of BP and TCPL are held at the Welding Engineering Research Centre at Cranfield University, UK. However since 2007 there have been no follow on contracts, the PhD researchers and some technical staff associated with the original work on X100 have moved on.

9.4 Compilation of Library of Existing X100 Welding and Materials Specifications

Existing X100 welding and materials specifications tend to be held as proprietary documentation by the operator companies and/or their pipeline welding contractors. This situation is general for pipeline welding even for pipelines in lower grade materials, although in the latter case, e.g. welding of X65 or X70 similar procedures have been used so widely, procedures and welding consumables selection are probably more easily understood although precise welding parameters are usually not transferable between contractors and need to be re-qualified for any changes of essential variables and for change of power source or welding equipment. Thus, welding procedure settings and specifications are generally tied to one particular contractor, one type and/or model of welding equipment and for a specific composition range, even within a single line pipe grade. For welding higher strength level line pipe, additional variables, although not necessarily declared or outside of the AWS/ASME “essential variables” limits, actually become essential as any attempt to weld outwith the qualified parameter envelope is more likely to result in a defective weld or a weld failing to achieve the required combination of mechanical properties. Experience of developing welding procedures for X100 has shown that welding parameters must be controlled with a greater degree of precision than for lower grades. Compilation of a library of welding and materials specifications would require a level of collaboration between several companies that would exceed that of any present joint ventures.

9.5 Induction Bending of X100 Pipe

The production of bends in high strength steel line pipe, either as factory formed induction bends or bends produced form pressed half shells and subsequently welded, has proved difficult and, to date, it appears that X100 induction bends have not been produced. Induction bends are produced by taking “mother pipe” of appropriate grade and wall thickness and induction heating a short length of the pipe as a “ring” while slowly pulling the pipe through the bend-forming machine to a pre-set radius. The induction coil is moved slowly along the pipe (or the pipe is pulled through a stationary induction loop) so that the heated ring moved along the length of the pipe. Hence, the heated ring moves along the pipe and undergoes deformation as the pipe progresses through the induction-bending machine. The heated ring, in which the steel is typically in the austenitic phase, is supported either side by stronger material which has been heated already and is cooling down and by material which has not yet been heated to the peak temperature by the induction heater. This technique results in the production of a smooth bend of specified radius and bend angle at the centre blending in to parallel tangent ends. The induction bend can be to any specified obtuse angle between 179º and 90º. It is not possible to manufacture acute angle bends by this method and these are not necessary since a 135º bend is typically referred to as a 45º bend.

There are metallurgical and dimensional factors to be considered in this process. Firstly the mechanical properties obtained in the formed bend will be a function of material composition, peak temperature during induction heating and cooling rate. The process is essentially one of hot

working so any cold working effects should be minimal. The final condition of the bend immediately after forming is quenched and tempered in the bent portion with a transition to the as-received condition of the parent pipe at each tangent end. Some bends may be supplied in this condition but others may undergo a tempering treatment typically at 580-600ºC to improve toughness. Where bends are manufactured from normalized or as-rolled steel pipe the subsequent tempering may be suitable for the whole bend and result in minimal microstructural and mechanical property variation between the bend apex and the tangent ends. However, higher yield strength pipes, such as X100, are usually formed from TMCP plate, so the combination of high yield strength, high toughness and good weldability are the result of ultra-fine ferritic microstructure obtained by accelerated cooling of the parent plate from the finishing stand during rolling. Such TMCP microstructures are not generally amenable to tempering at 580-600ºC as properties would deteriorate.
Any post-bend tempering would have to be carried out at a lower temperature to preserve the mechanical properties at the tangent ends but which may not fully temper the middle section of the bend.

Early proposals for mother pipe for X100 bends included a higher alloy composition pipe to withstand the induction bending and quenching and tempering but coupled with this proposal was the expectation of higher hardness and impact transition temperature with lower toughness throughout the bend and reduced weldability at the tangent ends. With the exception of a successful prototype of an X100 induction bend from SAW pipe, reported by Sumitomo Metal Industries Ltd and Dai-Ichi High Frequency, [60] it is not known if there have been any subsequent developments, and if so, if they have been successful. It is noted that in the BP Spadeadam operational trial an X80 5D induction bend was manufactured by Mannesmann Röhrenwerke [84] and included in the test loop.

There are relatively few induction benders in the world, particularly for the manufacture of larger diameter bends. Furthermore, some benders may not have control of the supply of mother pipe and in particular, mother pipe composition, so any venture into producing X100 ends would require close co-operation between the induction bender and X100 pipe mill.

Finally for induction bending, a thinning allowance must be added to the mother pipe scantling as the pipe wall will thin slightly at the extrados position during bend forming. Depending on the allowance, further alloying may be needed to maintain the required strength level in the formed bend and this will unfortunately detract from weldability at the tangent ends.

An alternative method of manufacturing bends is that of the pressed half shell technique, followed by double seam welding at the extrados and intrados positions. For large diameter bends, it would be necessary to hot-press the half shells and this is likely to modify the mechanical properties of the parent plate which would presumably TMCP material. Finally the effect of the seam welding process would need to be evaluated. Unless sophisticated manipulation equipment is available, sub-merged arc welding is unlikely to be feasible so welding by semi-automatic GMAW or FCAW would probably be the preferred method. In smaller diameter bends such seam welds would have to be made from the outside only. To date the author knows of no X100 bends made by the pressed half shell and welded technique.

Identifying induction benders or consortia of pipe-mill and induction benders having access to the necessary technology for X100 is currently an information gap.

9.6 Cold Field Bending of X100 Pipe

Cold field-bending is an established method of pipe bending during pipeline construction. The pipe to be bent is loaded into a hydraulic pipe bending machine, designed to bend a variety of pipe strength grades, typically up to X80, but with a decreasing limitation on wall thickness with increase of pipe grade. A unique die size is required for each diameter of pipe to be bent; typically a bend capacity of 30 mm (1.2 in.) in X70 equates to 25 mm (1.0 in.) in X80 and 19 mm (0.75 in.) for X100. Field bending machines are available in a range of sizes and each machine is designed for operating within a specific size range e.g. 813-1219 mm (32-42 in.) diameter.

The sequence of bending is that after insertion of the pipe into the machine, a series of "pushes" followed by a move-up of the pipe results in small incremental bends at each position. An internal mandrel assists in maintaining roundness and dimensional stability in the bent pipe. The force for each incremental bend is supplied by powerful diesel powered hydraulics transferring loads via a pin-up shoe and stiff-back arrangement.

For established pipe grades such as X52 - X80, a typical bend angle of 0.5º per ft. (0.5º per 300 mm) can be achieved and a maximum bend angle of around 12.5º can be achieved on a 40 ft. (12 m) pipe. This gives a bend radius of approximately 115 ft (35 meters) with tangent ends of typically 7 ft. (2.1 m).

The bend operation results in both elastic and plastic bending of the pipe; the "elastic" component being lost as spring-back after the release of load, the plastic component being the "net" bend angle. Spring back of X100 is assumed to be greater than for lower grades due to its higher yield strength.

In 2001, BP conducted bending trials at CRC-Evans, Tulsa on 914 mm (36 in.) diameter X100 in two wall thicknesses. [97, 98] It was reported that net bend angles of around 11.5º were satisfactorily produced and a larger total angle may have been possible but for the fact that generous tangent ends were deliberately left. Visual examination indicated that bends were smooth, dimensionally correct and without flat spots or wrinkles,

Following bending trials a comprehensive examination and test programme was conducted. Significant conclusions included that some increase in longitudinal yield strength and yield/tensile ratio occurred as a result of work hardening in the extrados regions and should be taken into account for any limit state design. Charpy toughness values on samples taken from the extrados of bends compared well (even after simulated strain ageing treatments) with toughness at the unstrained tangent ends; all values averaging between 170 and 200 joules and showing 100% shear fracture.

In subsequent X100 pipelay operations by TransCanada Pipelines Ltd at Godin Lake, field bending of X100 has been carried out successfully in winter conditions. [30, 31, 32] Tests and the field trials have proved that X100 can be cold bent successfully with existing equipment, although any scaling up of size or wall thickness may require larger capacity machines to be produced.

9.7 Defining Knowledge or Experience Gaps

It is probable that most first level "managing" or "pipelay" contractors will not have existing experience of working with high strength X100 line pipe. Although many operations involved in building a pipeline will be similar irrespective of grade, experience of some specific technology driven operations will be lacking and technology transfer from second level or specialist contractors and/or client will be needed to ensure success.

For welding of X100, several specialist contractors have access to the necessary technology, either through their own development programmes or, more generally from participation in fundamental welding development work with certain pipeline operator companies who have sponsored the development of X100.

There appear to be two or three leading X100 pipeline welding contractors, all of whom have participated in fundamental development work. Typically these include CRC-Evans and Serimax whose equipment has been used in the welding procedure development trials. Such companies are expected to have a sound knowledge of not only the "essential variables" defined by the welding codes but also of the additional essential variables that apply to X100.

The TransCanada Pipelines projects between 2002 and 2007 provide an indication that X100 field welding technology transfer between CRC-Evans, (whose equipment was used) and TCPL with other pipeline welding companies (Marine Construction and Louisbourg Pipelines) was successful, although TransCanada Pipelines Ltd engineers remained closely involved in a supervisory role.

Serimax successfully welded the girth welds in BP's X100 operational trial at Spadeadam. UK. It is not known if Serimax equipment has been used by others or if any further technology transfer has taken place.

Designers of X100 pipelines have little guidance from existing codes and operating companies intending to build X100 pipelines need to facilitate liaison between steel mill and pipe manufacturers, designers, first level (main) contractors and specialist second level contractors and regulators to ensure that each has a firm understanding of all important technical issues.

Sourcing of bend and fittings for X100 must be undertaken with care. At present it appears that X100 induction bands are not routinely manufactured and, as a default, X80 bends and fittings (with increased scantling to compensate for lower strength) are used. Development of genuine X100 bends and fittings should be encouraged if X100 is to be used more widely.

Experience to date has shown that X100 can be cold bent in the field, with apparently little degradation of mechanical properties. Trial bends were made as early as 2001 by CRC-Evans and some cold bends have been made successfully in the field in the TransCanada Pipelines Projects.

10. Practical Drivers and Resource Constraints in the Mills and the Field

10.1 Resource Constraints – Pipe Manufacture

Although development of X100 pipe began more than 15 years ago the driving forces prompting the original developments have not materialized into practical economic drivers for large-scale application. As such, much of the work involves limited fields of application, including trial pipe-lay operations, full scale fracture control tests and full scale operation trials that have been aimed at developing and demonstrating competence in handling the high strength line pipe and characterizing and testing its performance and properties.

Some potential projects, perceived in the 1990's as potential candidates for X90, X100 or X120 have either been and gone or have been developed using lower grades of line pipe such as X70 or X80. Examples might include Southern Algeria Gas, Kovykta (Russia) or possibly long distance pipelines in remote areas such as China. Developments in X100 developments and recent reports of limited trial production from China [57, 99, 100] suggests that high strength steels may be being actively considered for long distance pipelines.

Other areas, such as mainland continental Europe, already have an extensive network of high-pressure trunk pipelines for gas transmission and companies operating gas pipeline networks across EU country borders and beyond appear to have no incentive to consider line pipe grades higher than X80, although there has been a progressive move upwards in the last few years from X70 to X80 in some areas including the UK. Where such extensive pipeline networks exist in developed and relatively high population locations, there is less possibility to successfully exploit the higher tensile properties of materials such as X100 and, in some countries, technical requirements from remaining historic legislation may preclude application of higher strength line pipe at the present time. e.g. Requirements limiting yield to tensile strength ratios to a specified maximum are typical and would debar X90 or X100.

Situations where the perceived market for high strength pipe is seen to be restricted have a knock-on effect in that steel mills and pipe manufacturers are less incentivized to develop the steels and production techniques for the new materials, particularly where to do so would also require significant capital expenditure for new steel making, plate rolling and/or pipe manufacturing plant.

Therefore, constraints on production of higher strength pipe such as X90, X100 or X120 for some manufacturers may be

- inability to process and cast steel of requisite quality and cleanness, or
- inability to procure suitable steel slab from other sources,
- limitations on plate rolling to achieve the required combination of tensile, toughness and ductility, properties in all plate thickness ranges and, for pipe manufacture or,
- inability for procure suitable plate from other sources,
- limitations on pipe pressing capacity leading to restricted pipe size and wall thickness availabilty.
- physical limitations of pipe expanders for certain pipe diameters and wall thicknesses,
- achieving the required seam weld mechanical properties and toughness in SAW pipe.

From information submitted to this study by steel mills and pipe manufacturers, it can be assumed that probably 5 or 6 mills in the world have developed proven technology and procedures to manufacture X90 and X100 large diameter SAW pipe in either longitudinally welded or helical welded format but, even with these mills, there may be sizes (specific diameter/wall thickness combinations) for which specific production parameters have yet to be developed or for which equipment capacity limitations apply. In such cases, the prospective user needs to initiate early enquiries as pre-production trials may be necessary.

In the case of X120, no information beyond that published at conferences has been divulged and only limited responses were given to enquiries from this study. If any further development work has been done with this material it does not appear to have been publicized. Consequently it is concluded that the ability to manufacture large diameter X120 SAW pipe is probably confined to two or three experienced steel mills and pipe manufacturers. Developments may have been carried out by one or two more companies. There are no reports of any X120 seamless line pipe developments.

Comparatively recent programmes by two manufacturers of seamless pipe have resulted in the successful development of X90 and X100 seamless pipe in grades X90 and X100. [22, 23, 24, 25, 26, 27] Data submitted in support of including these materials in ISO 3183 and API Specification 5L indicated that the pipe is weldable with a high level of toughness. It is uncertain if significant production constraints apply but the present proven diameter limit for these pipes appears to be around 406 mm (16 in.) The application for which these pipes were intended was initially sub-sea (flow lines and risers) but the pipes may be suitable for wider applications. Again, prospective users need to begin early dialogue with manufacturers regarding availability of specific sizes of pipe. At present there is no indication that X120 seamless line pipe is being developed.

There is no known proven source of supply of X90, X100 or X120 line pipe in High Frequency Induction (HFI) Welded or Electric Resistance Welded (ERW) pipe nor of development of suitable hot-rolled strip at the strength range required for feedstock for these pipe processes.

10.2 Resource Constraints – Field

Responses to this study have shown that companies that have successfully completed pipelay projects with X100 or X120 are operator companies that have already made large investments in high strength line pipe technology, usually over several years or for more than a decade. Such companies have collaborated effectively with the pipe suppliers and with pipelay and welding contractors during the welding development phase. Specialist pipeline welding contractors who participated with operators and organizations like Welding Engineering Research Centre, Cranfield in developing girth-welding procedures will have a firm understanding of the additional welding variables that affect weld properties in X90 and X100 and of the level of precision required when applying the welding procedures, relative to welding lower grades. Such firms have a head start over others when field welding is to be undertaken although, as TransCanada Pipelines projects have demonstrated, successful technology transfer to other pipelay welders (using the same equipment) is possible.

Possible resource constraints in the field may include:

- Skilled girth-welding operators in sufficient numbers (this could be overcome by training).
- Welding engineer knowledge and experience of X90 or X100.
- Defining and recognition of proven welding equipment (which may include welding heads. control equipment and power sources).
- Evaluation of “alternative” welding equipment for suitability, (if offered by a contractor).
- Proving of “ alternative” equipment if accepted.
- Selection of welding consumables for girth welding.
- Proving of welding consumables and process by site simulated qualification testing.
- Specification and implementation of precision required for control of welding variables.
- Implementing power source pulsing parameters and waveform as a critical variable.
- Possible force limitations of internal welding clamp with some sizes of X90 or X100.

- Possible force limitations of on-site cold bending machines with some sizes of X90 or X100.
- Development and execution of tie-in technology including specifying welding process.
- Welding consumables for tie-in welding.
- Specification and supply of factory formed bends and fittings in X100 or lower grade.
- Design, specification and implementation of corrosion protection systems including cathodic protection.

11. Desired Performance for Offshore and Onshore Pipelines

11.1 Material performance targets – Parent pipe, HAZ and Weld

More than a decade of development work has enabled a general concept of material performance targets to be set for X100 for onshore gas transmission lines; however the fine detail of the steel and pipe specification will remain unique for each individual application. The publishing of ISO standard 3183:2007 [101] and the 44th Edition of API 5L [102] including, for the first time, standard requirements for X90 (L630), X100 (L690) and X120 (L830) is a starting point, but for each application the designer and contractor will inevitably prepare a detailed supplementary specification for the purchase order. The reason for this is that the international and API standards are consensus documents reflecting the best agreements possible in standards committees between steel-pipe manufacturers and user operators. Examples of this include a wider than desirable yield strength range of 150 MPa for X100 (min 690/ max 840) which, in a private purchase supplement, might be contractually narrowed down to 120 MPa, with a maximum yield strength of 810 MPa, to allow easier weld metal overmatching in construction. A further concern about the wide limits permitted by the ISO and API standards relates to the high limiting levels of yield to tensile ratio $R_{t0.5}/R_m$ of 0.95 (X90), 0.97 (X100) and 0.99 (X120). It is acknowledged that a footnote in the standard allows lower values for this ration to be negotiated for X100 and X120, an option which may well be exercised by purchasers.

Requirements specified in the standard for tensile strength of the weld seam should be readily met since these coincide with the minimum specified tensile values of 695 MPa (X90), 760 MPa (X100) and 915 MPa (X120) and should be readily achievable with the highly alloyed SAW weld deposits used in pipe mill welding.

The performance of the (typically extensive) seam weld HAZ in large diameter welded pipes remains an uncertainty as HAZ softening appears to be feature of these higher strength pipes. The early work of the late 1990’s included a number of ring expansion tests containing simulated defects and, later on, several burst tests have been conducted by different parties but not all have been reported in the public domain.

The present ISO 3183 and API 5L standards specify minimum requirements for Charpy toughness as a safeguard against brittle fracture (which are diameter related), so typically a 1219 mm (48 in.) diameter X100 pipe would require 54 J at 0°C unless a lower test temperature is specified. For an X120 pipe of typically 1422 mm (56 in.) diameter the requirement would be 108 J at the same temperature. Clearly values such as these are readily achievable in the pipe body but are eclipsed by the much higher toughness requirements to arrest running fracture in gas pipelines. The three tables of Annex G of ISO 3183 /API 5L unfortunately do not cater for arrest of running fracture in X90, X100 or X120 gas pipelines. The tables of Annex G are based on EPRG data with data validated to X80 (L555). So, for developers of gas pipelines in higher grades, the only option at present is to conduct full scale burst tests using gas of appropriate composition to simulate the lean or rich composition of the inventory of the future pipeline. The data from full-scale fracture control tests on X100 and X120 needs to be presented in the public domain so that the toughness guidelines of EPRG (and Battelle) can be extended. From industry heresay, it appears that the toughness requirements to arrests running fracture in X100 at typical sizes of 914 mm (36 in. diameter) and above may exceed the Charpy toughness that can be achieved in good quality pipe (where most pipe body figures can exceed 200J at 0°C or better. It is also important to note that the EPRG and Battelle guidance methods for resistance to running fracture are for lean dry natural gas and for rich gas compositions will be higher and possibly determined only by a full scale burst test.

The ISO 3183 / API 5L requirement for X100 seam weld and HAZ toughness are simply 40J at a test temperature of 0°C or lower, if specified. This is simply based on the requirements for materials greater than grades L555 (X80) or greater and may merit consideration of a higher specified level, given the actual Charpy toughness that can be achieved in the seam welds manufactured at the mill.

For gas transmission use, the drop weight tear tests (DWTT) will be required for each application. Data on X100 published to date suggests that achieving the required 85% shear area at a test temperature of 0°C should not be a problem but recent discussion within ISO TC67/SC2-WG16 / API WG 4218 highlights a worrying concern that DWT tests on modern high toughness steels frequently produce invalid results in that ductile fracture initiates from the notch tip, before changing to a regime of brittle rupture or in some cases followed by major plastic deformation without fracture. This behavior is currently the subject of an EPRG programme, which at present centers on lower grade and smaller diameter pipes rather than X100.
Where DWTT is specified at sub-zero temperatures, some suppliers declined to meet the 85% shear value on a contractual basis but volunteered to conduct the tests with results supplied for information.

The relatively new development of X90 and X100 seamless pipes by Tenaris, Sumitomo and possibly others was originally for offshore applications (flow lines and risers) but may find wider applications elsewhere. These seamless material in the quenched and tempered condition have now been proposed for standardization, having passed API letter ballot and now feature in ISO DIS 3183 [103] as grades L625Q (X90Q) and L690Q (X100Q) as shown in Table 11.1.

Table 11.1
Composition limits for X90Q and X100Q Seamless Pipe (ISO DIS 3183 – 2010) [103]

Steel grade (Steel name)	Mass fraction, based upon heat and product analyses % maximum									Carbon equivalent % maximum	
	C	Si	Mn	P	S	V	Nb	Ti	Other	CE_{IIW}	Pcm
L625Q or X90Q	0.16	0.45	1.90	0.020	0.010	a	a	a	b, c	as agreed	
L690Q or X100Q	0.16	0.45	1.90	0.020	0.010	a	a	a	b, c	as agreed	

a) unless otherwise agreed Nb+V+Ti ≤ 0.015%
b) B ≤ 0.004%
c) unless otherwise agreed Cu ≤ 0.50%, Ni ≤ 1.00%, Cr ≤ 0.55% and Mo ≤ 0.80%

The composition limits proposed in DIS 3183 are, as usual consensus values and footnotes in the table permit, specify additional limits for Cu, Ni, Cr and Mo and an upper limit of 0.004% B. This allows considerable manufacturing latitude so it is important that the purchaser and manufacturer reach clear understanding on the precise alloy composition CE_{IIW} and /or Pcm limits to be supplied and specified in a user purchase supplement. Data relating to the development of these seamless grades was provided to the API/ISO standards working group [104] prior to preparing DIS 3183 and some papers have been published.

Tensile properties for the X90Q and X100Q seamless pipes have also been standardized in DIS 3183 as shown by Table 11.2 (from DIS 3183) and target properties are identical with those for the TMCP larger diameter welded pipes.

The initial target Charpy toughness was ≥ 80J at -10°C and a pipe steel CTOD value of ≥0.25 mm at the same temperature. Figures from the development tests given in published material indicated that the target value was exceeded at the -10°C test temperature and that the 50% fracture appearance transition was between -55°C and -95°C depending on the alloy and individual pipe. This indicates that the minimum Charpy values specified in DIS 3183 /API 5L which are only 40J at 0°C up to 762 mm (30 in.) diameter can be more than easily met, but for demanding deep water applications, purchasers may seek a substantially higher value of CVN as an assurance of high metal toughness, despite sub-sea operating temperatures being higher than necessary to justify it.

Results published by Tenaris [105] indicated that high CTOD values can be achieved consistently from test pieces sampled from both the longitudinal and transverse orientations confirming a high strength and toughness combination in pipes up to 25 mm thick. If the ultimate objective of using X90Q and X100Q widely in deepwater sub-sea applications is to be realized, the next step would be to develop these products in thicker wall variants.

Table 11.2
Tensile Requirements for Seamless X90Q and X100Q pipe [103, 105]

Pipe	Yield strength, MPa (psi) $R_{t0.5}$		Tensile strength, MPa (psi) R_m		Ratio $R_{t0.5}/R_m$	Elongation, % A_f
	minimum	maximum	minimum	maximum	maximum	minimum
L625Q or X90Q	625 (90,600)	775 (112,400)	695 (100,800)	915 (132,700)	0.97 a	b
L690Q or X100Q	690 (100,100)	840 (121,800)	760 (110,200)	990 (143,600)	0.97 a	b

a Lower $R_{t0,5}/R_m$ ratio values may be specified by agreement for L625Q or X90Q and L690Q or X100Q
b Elongation determined by formula of ISO 3183 / API 5L

Published results of one development programme also provide description of the microstructure comprising fine packets of greater than 60% low-carbon martensite, the complete microstructure being a fine martensite-bainite package with carbide precipitation at grain boundaries.

Information has also been published [22, 23, 24] about trials to prove the weldability of X90Q/X100Q, specifically simulating techniques that would be used for joining top-tension riser pipes. Root and hot passes were welded using GTAW-P with a consumable of the AWS ER 100 Class followed by fill and cap passes utilizing the GMAW-P process with solid wires of AWS classifications ER 100 to ER 120. CTOD testing was carried out on test welds to API 2Z. The published paper indicates that while some of the wires produced welds with a yield strength exceeding 810 MPa, others failed to meet this target, either narrowly or by a wider margin but with a trade-off in terms of tensile elongation. This suggests that the same level of precision used for narrow-gap welding of larger diameter welded pipe should also be applied to these grades of seamless. The weld microstructures were reported as being fine bainite-acicular ferrite.

Weld metal impact test results at 0°C ranged from around 90J at the low end up to values of more than 150J. Even higher values were consistently measured at the FL, FL+2 and FL+5 mm positions typically being 90J again at the low end (FL) up to 280-290J in some FL+5 tests. CTOD validation trials showed a greater spread of results, depending on the welding wire used to deposit the weld.

As the intended initial application for X90Q and X100Q was the offshore industry, particularly for deep water flow-lines and steel risers it is probable that initial orders will be directly between major oil/gas companies and contractors and the respective seamless pipe manufacturers therefore allowing properties to be customized to the particular application.

Tenaris proposed an X100 base metal and girth metal property guarantee [105] summarized in Table 11.3.

Other technology development issues that should be investigated by companies intending to use X90 or X100 seamless pipe in deep water offshore applications include fatigue performance of girth welds in risers, possible effects of internal corrosion-fatigue depending on the well fluid within the pipe, effects of cathodic protection and over-protection (possible effect of hydrogen embrittlement). These phenomena tend to be common to all deep water pipe applications and should be investigated irrespective of pipe grade. However it is possible that some effects are accentuated with higher strength pipe, so trials conducted previously on lower grade pipes may warrant being repeated with these new materials.

Table 11.3
Base Metal and weld Metal Values (Tenaris Guarantee)
Seamless X100 Weldable Pipe for Risers

Property	X100 Base Material	Weld Metal (WM, FL, & FL+1 mm
Yield strength MPa (ksi)	≥ 690 (100)	≥ 690 (100)
Tensile Strength MPa (ksi)	≥ 760 (110)	
Y/T ratio	≤ 0.96	
Elongation %	≥ 18	
HV10 max	≤ 325	
HV10 Average per row		≤ 350
CVN J @ -40°C	≥ 80	
CVN J @ -10°C	≤	≤ 80
Min Ind CTOD mm @ -10°C	≥ 0.25	
CTOD mm Ave @ 0°C		≥ 0.15

11.2 Unique Requirements For Each Application

Each pipeline, irrespective of the grade of line pipe used in its construction is unique and, although there are standardized methods and codes for designing pipelines, the final design details will be individual to each one. Factors affecting the design include design stresses, including hoop and longitudinal stress from internal pressurization, further longitudinal stresses from externally applied loads such as foundation shift, thaw of permafrost, seismic movement, lateral movement arising from seabed fluctuations in offshore submarine pipelines and expansion/contraction cycles from high diurnal temperature changes in overland exposed pipelines, The pipeline wall thickness will be influenced by factors such as design factor ranging from 0.3 YS in highly populated cities or urban areas through to the commonly used 0.72 YS and in recent years to a design factor of 0.8 YS for an increasing number of pipelines.

Other factors affecting wall thickness include hydrostatic head variation in mountainous regions, additional corrosion allowance (and hence inventory carried by the pipeline) and fatigue considerations from pressure cycling especially phenomena such as line-packing in gas pipelines, and fluctuating stresses in sub-sea flow lines and top tension steel catenary risers. These factors need to be considered irrespective of pipeline grade and merit special consideration for the high strength line pipe such as X90 through X120 where the apparent advantages of the higher grade material may not be fully realized in every instance. Examples of this may include marginal sour service, where higher hardness values in welds may render the stronger material vunerable to premature failure or where stresses are fluctuating in service and the required fatigue life may not be obtained at the higher stress to justify the stronger material. The effect of stress concentration at girth welds occurs in a zone of metallurgical microstructure transition where welding may have induced defects in weld metal or at the fusion line junction between the weld and parent metal that has itself been transformed into a HAZ. This region must be studied with care for all pipeline materials but should be thoroughly investigated for pipelines to be built in high strength line pipe. The growing application of strain-based design for pipelines demands attention to the form of the tensile stress-strain curve for the material and, in the case of the newer high strength steels such as X100, particularly when manufactured from lean composition, low carbon, micro-alloyed TMCP pipe, where the yield to tensile ratio is exceptionally high, to the total strain capacity of the steel. Thus, the user requirements for using a high strength line pipe will be unique in all cases and the criteria for the design and hence the material specification will need to critically examine the factors discussed in this section.

11.2.1 Setting Flaw Acceptance Levels

Pipeline construction codes such as API 1104 [106] and BS 4515 [107] traditionally set flaw acceptance levels based on workmanship standards relating to imperfections that can be measured easily in the case of surface breaking defects or whose type and size could be estimated to varying degrees of accuracy by methods of non-destructive testing such as magnetic particle testing (MT), radiographic testing (RT) of ultrasonic testing (UT) in the shop and in the field. The same methods would be employed in the pipe mill, particularly for welded pipe, while inspection of seamless pipes would (and still do) utilize eddy current testing with MT.

The full specification of workmanship defect acceptance levels may be found in the referenced standards and the following examples indicate the approach used which was applied irrespective of pipe grade or the design stresses in the pipe. The following examples shown in Table 11.4 are taken from BS 4515-1:2000.

Even before the advent of high strength line pipe such as X100, a fracture mechanics approach was being adopted for many pipelines and relating a toughness parameter of the steel (measured in the parent metal, weld metal of HAZ) to the stress applied to the individual pipeline. Initially this approach was sometimes used to obtain waivers where a flaw exceeded the arbitrarily imposed criteria based on workmanship standards but could be shown to be left safely under the pipeline operating conditions.

For many years, the defect acceptance based on workmanship criteria served the pipeline industry well as pipelines were constructed in lower grade steels and pipeline girth welding was a predominantly manual process. The workmanship acceptance standards are based on historical criteria that are acknowledged to be largely empirical and place primary importance on imperfection length. The surface breaking, geometric and volumetric defects were more commonplace and readily detected by visual inspection, MT and/or RT. Poor attention to welding procedure could result in weld or HAZ cracking or lack of penetration or lack of fusion defects in the weld metal. Poor care of welding consumables could lead to porosity in welds. However, it was cracks or crack-like defects that remained a main concern and although RT would frequently detect cracking, cracks or lack of fusion defects that were not favourably oriented with respect to the X or gamma radiation could remain undetected.

Before the advent of the high strength line pipe such as X100, step changes were taking place in the pipeline industry and since the 1980's the advent of TMCP resulted in line pipe with leaner composition of superior weldability, higher toughness and less propensity to hydrogen cracking. This was true for a range of line pipe steels from X65 (L 450) and higher grades and encouraged the development of X80 (L555). Also in the 1960's development of mechanized GMAW girth welding began and, in the intervening years, has progressed to a versatile precision process. The use of narrow gap bevels, of high quality GMAW weld metal deposited via a precisely controlled low hydrogen gas shielded welding process has firstly reduced repair rates and such defects that are produced are predominantly of a different type to the older processes. So there are fewer incidences of inclusions or porosity and almost zero level of slag entrapment so the types of defect of most concern are crack-like lack of fusion and lack of inter-run fusion, lack of penetration, especially at the root, undercut and bead profile. In recent years, traditional pipeline radiography has given way to increasing use of automated ultrasonic inspection (AUT) and this technique is well suited to inspect girth welds made by mechanized GMAW.

The AUT technique is well suited to detection and identification of planar imperfections such as cracks, lack of root or sidewall fusion and can often provide a rough estimate of defect dimensions and defect type. This data can be linked with parameters such as material toughness and CTOD data for the zone where the defect has been located and use of fracture mechanics analysis and fitness-for purpose criteria provides a method for determining the defect acceptance size limit that is appropriate to the weld detail, given that the stress level is known since the method can evaluate the significance of both height and length of imperfection.

This methodology for setting alternative flaw acceptance levels may be found in Appendix A of API Standard 1104, [106] in BS 7448 [108, 109, 110] , BS 7910 [111] and DNV OS-F-101 [112] (which, in turn, refers to DNV RP's C203 and F108)

Fitness-for-purpose criteria derived in accordance with these alternative methods may allow more larger imperfection sizes but each case is dependent on material characteristics such as CDOT or J value obtained specific procedure qualification tests, stress analysis of the pipeline detail and verification by inspection. It is apparent from the large numbers of CTOD testing that have been reported in the X100 development programmes, that this fitness-for-purpose approach is to be used (or has been used). However, of the published papers surveyed, no examples of typical allowable defect sizes have been found so this data is assumed to be proprietary.

Table 11.4
Examples of Defect Acceptance Criteria based on Workmanship [107]
(Not considered suitable for High Strength Pipelines)

Imperfection	Acceptance Criteria
External profile	Excess weld metal (reinforcement) shall be uniform and shall merge smoothly with the parent metal and shall extend beyond the original joint preparation by not more than 3 mm on each side. In no area shall the weld face be lower than the adjacent pipe surface.
Internal profile	The root bead or any concavity shall merge smoothly into the adjacent surfaces.
Root penetration	Not to exceed 3 mm or a more stringent limit, if specified by the employer.
Root concavity	Length not to exceed 25 % of total length of weld. Depth not to exceed 10 % of pipe thickness or 1.5 mm whichever is the smaller but, at no point, shall the weld, including cap reinforcement, be thinner than the pipe thickness.
Root undercut Shrinkage groove	Length not to exceed 25 mm in any continuous weld length of 300 mm or not to exceed 1/12 of the total length of the weld when this is less than 300 mm. Depth not to exceed 10 % of pipe thickness or 1.5 mm whichever is the smaller.
Incomplete root penetration Lack of root fusion (single side welds only)	Length not to exceed 25 mm in any continuous weld length of 300 mm or not to exceed 1/12 of the total length of the weld when this is less than 300 mm.
Lack of root fusion (single side welds only)	Length not to exceed 25 mm in any continuous weld length of 300 mm or not to exceed 1/12 of the total length of the weld when his is less than 300 mm
Cracks	Not permitted.
Cap undercut	The toes of welds shall blend smoothly and gradually into the parent metal. Length not to exceed 50 mm in any continuous weld length of 300 mm or not to exceed 1/6 of the total length of the weld when this is less than 300 mm. Depth not to exceed 10 % of pipe thickness or 1.5 mm whichever is the smaller.
Elongated linear porosity in root run (hollow bead) Shrinkage cavity Lack of inter-run fusion Lack of side fusion Elongated inclusions Parallel elongated inclusions	Length of weld affected not to exceed 50 mm in any continuous weld length of 300 mm or not to exceed 1/6 of the total length of the weld when this is less than 300 mm. Width of elongated inclusions not to exceed 1.5 mm.
Porosity (other than elongated porosity in root run)	Not to exceed a total area when projected radially through the weld of 2 % of projected weld area in the radiograph consisting of the length of the weld affected by the porosity, with a minimum length of 150 mm, multiplied by the maximum width of the weld. An isolated pore greater than 25 % of the pipe thickness or 3 mm, whichever is the smaller, in any direction shall be considered unacceptable.
Isolated inclusions (copper, tungsten or non-elongated slag)	Width of an inclusion not to exceed 3 mm or half pipe thickness, whichever is the smaller. Total length of inclusions not to exceed 12 mm in any continuous weld length of 300 mm and not more than four inclusions of maximum width in this 300 mm length. Adjacent inclusions shall be separated by a minimum distance of 50 mm.

It is also noted that API 1104 Appendix A and DNV OS-F101 exclude welds subject to fitness-for-purpose analysis, where longitudinal strain exceeds 0.5% and therefore setting alternative defects acceptance levels in strain based design pipelines in X100 would require special care.

Use was made of various fracture mechanics based techniques by BP and Advantica (now GL Noble Denton) to size deliberately introduced defects into the X100 operational trial at Spadeadam. This trial is reported elsewhere [83] and was conducted on a 48 in diameter X100 pipeline approximately 1 km long with a design factor of 0.8 which was subjected to pressure cycling over a two year period. The defects that were introduced included volumetric corrosion defects, mechanical damage, rock dents, arc strikes and girth weld defects comprising lack of sidewall fusion, lack of root penetration and porosity. A girth weld repair was also included. Methods used to size these "defects" included Annex G of BS 7910 (Method LPC-1) for the isolated corrosion defects. A combination of techniques of Annex G of BS 7910 and study data from PRCI Project PR-273-9603 was used to assess interacting defects and assessment of the fatigue strength of the volumetric corrosion defects was by data generated by Advantica under PRCI project PR-273-0323 based on estimation of an elastic stress concentration factor (SCF) for an idealized defect as a function of defect dimensions. Workmanship based limits (modified by BP company specifications) were also used as the acceptance standards for girth welds in the X100. Also an EPRG weld defect acceptance criteria approach (that is technically validated only to X70 but already modified for X80) was used to determine sizes of defects such as lack of side-wall fusion, lack of root fusion and porosity. Hence the fracture mechanics/ECA approach was used in reverse to calculate the size of defect that was tolerable in the trial, rather than as conventionally used to calculate the maximum size defect that would be allowed in a service pipeline. The trial completed after 2 years operation and it is known that subsequent laboratory testing of component sections has taken place but no results have yet been reported in the public domain.

11.3 Knowledge and Experience Gaps

Developments since the late 1990's indicate that production and pipe-lay development of X100 welded pipe has been well researched and that much data has been presented in the public domain; however it is believed that much information remains proprietary. Sections of X100 pipe have been incorporated into functioning pipelines by TCPL as a successful pipe-lay fabrication exercise and BP have carried out a two year operational trial on an X100 pipeline containing known defects and pressured to 0.8 design factor in a cyclic manner. This trial is understood to have been successful but, as yet, no results of subsequent laboratory tests have been published. Technology items that merit further attention for the welded pipe include:

- Further studies of the seam weld HAZ softening and reduction of the extent of softening
- Data on full scale fracture control tests on X100 (lean gas) and incorporation with EPRG
- Fracture control test data with rich gas (may be a single company project)
- Review of DWTT behavior of X100 (test validity)

It is possible that some questions remain to be addressed with X120 but the only data available to this PRCI survey was from published papers, so review has been more limited.

The recent developments of X90Q and X100Q seamless pipe appear to have been thorough and the objective for its use was well defined. Characterization of the materials (in the limited size range) has also been thorough and the grades are being standardized. Items that would benefit from more development may include:

- Additional diameters and greater wall thickness for deep-water*
- Study of effects of cathodic protection/overprotection and hydrogen embrittlement
- Fatigue testing if to be used for deep-water risers*
- Corrosion fatigue testing for aggressive well fluids
- (*Subject to identified industry need)

All higher strength steels e.g. X90 and X100 would benefit from better guidance on defect acceptance levels based on:

- Validated workmanship criteria (where possible for simple applications)
- More data (data bank) on allowable defects permitted by ECA methods

11.4 NDE Methods and Acceptance Levels

NDE of large diameter girth welds in pipelines in materials such as X100 will be predominantly by automated UT with enhanced signal processing. This proven method is already in regular use for large diameter pipeline construction and provides rapid feedback to front-end welding. Furthermore the technique can be set up with sufficient sensitivity to identify, characterize and size imperfections accurately. AUT output can therefore be linked successfully to assess imperfections against ECA criteria.

Other methods may continue to be used, including radiographic testing (via crawler systems) but probably to a decreasing extent.

12. Identification of Knowledge and Experience Gaps – Project Prioritization

12.1 General

Studies for this review show that much knowledge and experience has been acquired with X100 SAW pipe over a period of some 15 years, although, at the present time, such experience resides with a select group of steel-pipe mills, oil-gas companies, research organizations and contractors. Outside of this select group, both knowledge and experience of X100 is very limited and for other organizations to embark on a project using X100 entails a steep learning curve.

Enquiries made by this PRCI project about the higher strength X120 elicited no response and the small amount of information presented about X120 in this review was gleaned from a few conference papers published by ExxonMobil and their material suppliers. It is therefore likely that any company intending to utilize X120 for a pipeline will need to enter into technical collaboration with ExxonMobil, both to acquire the necessary technical expertise and to clear patent and licensing issues. The bulk of this review relates to X100.

This review has shown that, for X100, collaboration between steel-pipe mills, several oil-gas companies, universities and research organizations has been fruitful and has resulted in early trials of steel compositions and processing techniques leading to viable line pipe on a manufacturing production scale, albeit with limited amounts of material being produced and used to date.

12.2 Knowledge/Experience Gaps – Mill and Shop Welding

There is still some way to go in respect of X100 product optimization. In SAWL X100 pipe, the longitudinal seam weld is generally made with more highly alloyed steel filler wire and its toughness is generally inferior to that of the parent pipe. This does not appear to have caused any significant problems in the (limited) applications of X100 to date but it is recognized that, in the girth/seam weld intersection, the effects of weld dilution result in microstructure, hardness and mechanical properties that are different from the properties and characteristics of the bulk of the girth weld.

The SAWL pipe parent metal X100 generally comprises TMCP plate (Q & T would be an option, although probably uneconomical) and the fine metallurgical microstructure and low-carbon micro-alloyed composition have generally translated into high toughness line pipe with Charpy values frequently exceeding 200J even at temperatures of -20°C or lower. In some cases Charpy energy at - 20°C can be closer to 300J. Despite such inherent high toughness in the X100 pipe, verbatim reports of fracture-control (full-scale burst) tests indicate that automatic arrest of running fracture in some high-pressure gas pipelines cannot be guaranteed, necessitating the use of separate crack arrestors which negates some of the economic advantage of using X100.

More recently, there has been some production of SAWH X100 line pipe but little information has been provided on the base material composition or product form. No information has been provided about the helical seam welding fillers or weld property details. This is defined as an experience gap requiring further work and/or disclosure of existing data.

Seam welding of large diameter line pipe (both SAWL and SAWH) in the pipe mill utilizes the SAW process with multiple large diameter fillers wires in a tandem type arrangement with all wires feeding the same weld pool . The high arc energy that is characteristic of this process results in a slowly cooling weld pool and extensive HAZ. Softening of part of the HAZ indicates a line of potential weakness in the X100 that appears not to have been sufficiently investigated. At present there is no evidence in the public domain that the softened line in the X100 HAZ has contributed to any premature failure in a section of pipeline, although no sections of pipeline installed to date (except for BP's Spadeadam trial) have utilized the full potential of X100 in terms of design factor. Results of post-test examination of the BP Spadeadam materials have not yet been published.

12.3 Priority Needs – Welding Process and Consumables (Mill And Shop Welding)

Mill welding – The development of lower alloy SAW filler wires for pipe seam welds should be considered as the present highly alloyed seam weld deposits (containing up to 2% Ni) result in greater hardening in the intersection with the girth weld. It is acknowledged that the pipe manufacturer has a difficult task in achieving the required levels of high strength and toughness while producing the line pipe in an economic way (i.e. SAW line pipe is produced by depositing large unit volume SAW deposits in a single pass from the inside of the pipe and the same from the outside). An alternative would be to use a lower alloy filler wire and to make the welds in a series of smaller deposits at lower unit heat input. This could result in high toughness seam welds with a fine structure (as per girth welds) and an improvement of toughness and a less extensive HAZ. However, this would impact on the economics of pipe manufacture with significantly increased welding time for each pipe. The effects on production economics would extend beyond X90/X100 as the same welding lines are typically used for all grades manufactured in a pipe mill. The alternative of having a welding line dedicated to X90/X100 also carries significant economic implications.

Mill Welding – Development of bespoke welding consumables for seam welding X90/X100. At present the idea of tailoring welding consumables to a particular application is difficult to specify precisely. Applications considered initially for X100 included high-pressure gas pipelines in arctic regions but the use of this material could equally apply to other long distance gas pipelines, in temperate, or equatorial temperature zones and in widely diverse zones of habitation. The ambient operating temperature and the pipeline inventory (e.g. lean or rich gas) will determine the pipeline design premise and hence the toughness requirements. This, in turn, will influence the properties required of the weld and the consumables and technique required to produce the girth weld. At present, the absolute need for the option of developing bespoke welding consumables is uncertain but will be driven by user operator need.

Mill welding - Quantification of the effect of HAZ softening. The wide HAZ and associated line of local softening created by the seam welding of X100 remains a topic of concern. Although no service failures associated with this line have been reported in the public domain it may because the field applications of these high strength pipes have not tested the softened zone exhaustively. Early trials using constraint based fracture mechanics [10] suggested that the softened zone could be tolerated but some quantification of the extent and effects of the softened zone (perhaps from examination of fracture control tests and/or the BP operational trial, if available) would provide relevant design data and build confidence.

Mill welding – Mitigation of extent/elimination of HAZ softening. The seam weld HAZ softening is governed by (a) the composition and metallurgical condition of the parent pipe and (b) the thermal cycle of the SAW seam welding processes. The composition and condition of the pipe parent metal should be considered as already optimized and fixed and generally comprises a low-carbon, lean composition, micro-alloyed TMCP steel. This cannot easily be changed. The other main variable is welding heat input which is currently high, resulting from multiple wire SAW systems designed to deposit the seam weld quickly and economically. A change to lower heat-input or multi-run welding in the pipe mill will certainly reduce the extent of the seam weld HAZ but may not be economical. Any change to seam welding processes (other than those such as SAWL, SAWH, combination GMAW/SAW longitudinal seam (COWL), combination GMAW/SAW helical seam (COWH) or high frequency electric welding (HFW), as specified in standards such as API 5L / ISO 3183 would run the problem of manufacturing a non-standard line pipe which may not be accepted by regulatory authorities. To date there has been no development of HFW welded X90/X100 pipe which might be a development option for lower wall thickness, small diameter pipes, if required. A further option may be to use the COWL process with more extensive use of the gas metal arc process to weld additional passes over and above the seam weld root. This would appear to not conflict with the API/ISO definition of COWL welding although the GMAW element of COWL was not originally considered to such an extent.

Shop welding - Development of welding consumables and techniques for pipe-fitting welds. At the time of this review, there had been little development of pipe-fittings to match high strength line pipe such as X100. This itself is a technology gap particularly in respect of induction bends, fabricated bends, elbows, tees and flanges. This lack of compatible in-line fittings will inhibit the use of X100 as the alternative is simply used of heavier wall, lower strength items resulting in thickness mismatch and awkward transition joints. In some instances, the strength transition will have to be accommodated in girth welds and design of the weld joint will be of paramount importance. It is acknowledged that one manufacturer has made a prototype X100 induction bend, proving the feasibility of the process but the diameter and wall thickness range over which such items can be produced remains uncertain. Hence additional diameter/ wall thickness combinations should be produced so alloy combinations, weldability and mechanical properties can be evaluated. The development of optimized girth welding procedures (and if necessary, consumables) should proceed in parallel with the in-line fittings. It is possible, that since the Cranfield work of 7-8 years ago, improved GMAW and/or FCAW consumables may have been developed for use in shop-fabrication (and in field repair and tie-in techniques) but, if so, they have not shown up in this survey. The development of set-on fittings for X90/X100 pipelines is a separate issue but one that needs to be defined for clarity. Fittings such as weld-o-lets and set-on nozzles/flanges can probably be designed to be compatible with X90/X100 in existing weldable materials and with a thicker scantling. Items such as this are often heavy section to account for their set-on format and to compensate for material removed from the main pipe to which they are welded. The key to using such items will depend on suitable welding consumables being available for the high strength deposits required. Again, it is possible that existing high strength SMAW or GMAW consumables may be sufficient but the survey indicated that the FCAW consumables used in the Cranfield work [70] produced deposits of insufficient strength. In addition to possible welding consumables development, modeling of typical set-on connections with finite element analysis of the welded joints would produce useful design data.

12.4 Priority Needs – Welding Processes, Consumables and Parent Metal – Pipeline Construction

The successful field application of X100 by TCPL and in the BP operational trial at Spadeadam indicates that suitable welding consumables exist for mechanized GMAW girth welding of X100 under field conditions. Variation of either parent pipe composition (within the broad limits for X100 as specified by API 5L or ISO 3183) or welding procedure may invalidate the forgoing assumption and require new welding consumables and/or conditions to be qualified.

Experience of the TCPL trials demonstrated that the current mechanized GMAW processes (developed by Cranfield for TCPL and BP) can be effectively transferred to field contractors (e.g. CRC-Evans, RMS Welding and Louisbourg Pipelines. The BP operational trial indicated that Serimax's procedures were sufficiently robust for field use. However, there may be scope to improve field welding productivity and for the welding parameter envelope to be widened and better defined. The precision with which GMAW-P welding parameters must be set and the close tolerances required for other parameters suggests that, at high production rates for field welding, there would be little margin for wider parameter limits for satisfactory welding.

The complement of mechanical properties required of X100 pipeline welds will always be stringent and this may set the material apart from lower grade line pipe material, (other than perhaps X80). Since the most probable application is high-pressure gas pipelines, concurrent property requirements will be high strength, exceptionally high toughness and high values of uniform strain (the latter especially for strain based design pipelines). Achieving this combination of properties consistently depends on controlling a range of variables extending beyond the conventional "essential variables" defined by codes. The relatively wide limits of steel composition for X90 through X120 allowed by the API and ISO standards, introduce an element of variability that, along with welding process and consumable variations will affect the microstructure and property balance of the weld deposit. These elements are interdependent and although the variables may not be published in a conventional sense any prospective user of these high strength line pipes needs to qualify materials and procedures with great care.

A major technology gap is the absence of generally available X100 fittings including induction bends, reducers, tees and flanges which leads to the use of X80 fittings at present. The reporting of one attempt to manufacture an X100 induction formed bend is encouraging but development work on matching strength fittings is needed and, once such fittings are available, specification limits should be written into established standards.

Trial tie-in and repair welding procedures were conducted at Cranfield using SMAW root and FCAW-G fill and cap, but although depositing sound weld, yield and tensile strength from the Filarc 118 /ESAB Tubrod 15.09 cored wire did not meet the minimum 810 MPa yield strength level. TCPL's approach was to use an E55010-G cellulosic coated SMAW electrode for the root run, followed by an SMAW hot pass with a Lincoln LHD 100 (E69018-G) low hydrogen vertical down SMAW electrode, then filling and capping with Böhler BVD 110 LHD E72018-G) electrode. A procedure using this combination was qualified for Westpath and Godin Lake projects although, at Stittsville, the Böhler 110 electrode was replaced with a higher strength BVD 120. Also an alternative repair/tie-in technique was qualified for Stittsville of a GMAW STT® root using a Thyssen K-Nova wire, followed by a mechanized FCAW fill and cap using ESAB Tubrod 15.09. For the BP Spadeadam operational trial, Serimax qualified a series of repair and tie-in procedures based on SMAW STT® root with Lincoln Pipeliner® 80S-G electrodes followed by FCAW-G with ESAB Tubrod 15.09. Since the Tubrod 15.09 formed the bulk of the under-strength weld deposit in the Cranfield trials but features as a major element in some subsequent repair/tie-in welds, its properties merit further investigation. Additionally this is an area where development of a higher strength FCAW consumable for X100 is needed. The existing consumables may suffice for X90.

12.5 Priority Needs - Double or Multiple Jointing in the Mill or Shop and in the Field

Shop welding - Development of high toughness double jointing techniques. Experimental work to date has not included development of double jointing techniques and all X100 has been supplied as single joints (pipes). For several other grades of pipe, there is an increasing trend of supplying double joints where it is possible to transport pipes of up to 24 meters (80 ft.) to the field and, generally for smaller diameter pipes for offshore J-Lay operations. Where such pipes can be used, the pre-existing double-joint weld obviates the need for a field weld, thus accelerating the rate of pipe-lay. It should be noted that difficulties of transporting large double jointed pipes, particularly some in urban areas, implies limited use of this technique but for some remote long distance pipelines, sections built in or utilizing double joints would be feasible. However, the double joint girth welds manufactured in the pipe mill must meet all specified requirements of the pipeline welding code (e.g. API 1104, BS 4515, CSA Z662). Traditionally mill-manufactured double joints have been made with the SAW process with pipes rotated and welded in the 1-GR position. Although the welding will probably be by single wire SAW, rather than the multiple tandem techniques used for mill seam welding, more weld metal is deposited (due to the wider weld preparation than used by GMAW in the field) and the HAZ of the double joint girth will be more extensive. If double joints are to be made in the pipe mill, there is a need to optimize the SAW process, welding consumable and procedure to ensure that all girth weld requirements specified in pipe welding codes can be met, that such double-joint welds are thoroughly characterized and that HAZ softening is minimized. Alternatively, pipe mills intending to supply X90/X100 double joints could consider adaption and used of mechanized GMAW procedures thereby providing a closer match to field welds. Use of enhanced mechanized GMAW such as Cranfield CAPS dual tandem system could be considered.

Field welding - Development of high toughness double jointing techniques.

12.6 Priority Needs - Welding To Fittings and Tie-In Welding

- Development of genuine X100 fittings including bends, reducers, tees and set-on attachments. See Section 12.3
- Design of weld connections between X100 pipe and lower grade fittings such as bends,
- Development or optimized selection of welding processes and procedures for pipe/fittings
- Improved welding consumables and techniques for X100 tie-in welding
- Improved welding consumables and techniques for X100 repair welding

12.7 Onshore Versus Offshore Pipeline Welding Priorities

- Definition of diameter and wall thickness manufacturing range for SAWL and SAWH pipe. At present the limited production of large diameter SAW pipe in both SAWL and SAWH forms has been in a limited diameter range, typically 762-914 mm (30 – 36 in.) although one order of 1321 mm (52 in) has been manufactured. The manufacturing/availability envelope of diameter and thickness needs to be established and made available by manufacturers so operators can select grades and sizes accordingly.

Where diameter/ thickness break points affect steel composition (e.g. thicker wall pipes may need higher alloy content) supplier- purchaser dialogue is required.

- The current size range for seamless X90/X100 is fairly limited but is indicated by the published work by Tenaris and Sumitomo. When/if these products are produced in a wider range of sizes the manufacturing/availability envelope needs to be established and made known to prospective purchasers.
- Onshore pipeline welding priorities are as discussed earlier and may be summarized as:
  - Improvement of pipe seam weld and associated reduction of HAZ softening
  - Improvement and/or better definition of field welding parameter envelope
  - Improvement of girth welding productivity
  - Double jointing techniques for use in mill and field
  - Possible improvements in main line welding consumables to optimize balance between strength, ductility and toughness.
  - Improvement of repair and tie-in welding procedures and possible development of higher strength FCAW-G welding consumables
- Offshore pipeline welding priorities (currently assumed to relate to seamless X90Q/X100Q line pipe intended for risers and flow line (it is assumed that large diameter X100 will not find application offshore).
  - Field qualification of 2G position welding procedures for J-Lay
  - Tests to determine fatigue performance of X90/X100 girth welds in air and in seawater
  - Corrosion-fatigue tests for X90/X100 flow lines or risers for aggressive well streams
  - Collapse testing of X90Q/X100Q seamless pipe
  - Electrochemical studies of weld/HAZ/parent pipe zones for corrosive well streams.

12.8 Priority Needs - Welding Process Development or Refinement

Work to date has demonstrated the effectiveness of the mechanized GMAW process for field welding high strength pipe such as X100. At the present time it is unlikely that any major change of welding process is necessary for main-line welding. The mechanized GMAW is now an effective, high productivity method of field welding, capable of making sound girth joints with low repair rates. In the foreseeable future it is unlikely to be supplanted by any higher productivity process. Note, investigations of one-shot welding processes in the 1990's revealed no serious competitor to mechanized GMAW. Further development of the tandem and dual tandem mechanized GMAW process offers the possibility of higher productivity welding of X100. This may be achievable with existing welding wires but development of improved wires remains an opportunity.

Development of improved FCAW cored wires for repair and tie-in welding should be considered a priority as the widely used FCAW wire produces weld deposits that are deficient in yield strength relative to X100. Further development to optimize SMAW/ SMAW-FCAW, GMAW and FCAW techniques for both repair and tie-in welding would be beneficial.

12.9 Anticipated Trends in X100 Development

The present review has been unable to determine future trend in X100 development in respect of the large diameter welded line pipe. This is probably due to the small extent of use of X90, X100 and X120 to date and suggests that pipe manufacturers might be reluctant to embark on further developments of these materials until they see more evidence of a viable market. Any initiative for further development of these pipe grades by manufacturers is most likely to be promoted by a user company demonstrating serious intent to use high strength grades on a pipeline project rather than user industry consortia embarking on further evaluation trials.

The X90Q/X100Q seamless line pipe development was initiated by two leading pipe mills, originally aiming for a niche market in the deep-water offshore industry. One developing company launched the development with in-kind assistance from potential user companies. Within the limited size range in which X90Q and X100Q have been produced supporting technical data on material composition, microstructure, properties and weldability has been made available. Further development will depend on the uptake of these materials for the intended purpose or for wider applications. An indications of possible technology gaps on which further work should be carried out is given in 12.7. Again, the manufacturers will want to see signs of a viable market for this product if further development work is to be undertaken.

This review is unable to comment on further development trends in X120 welded pipe as there is only limited information in the public domain about this product and its use. Furthermore, although being standardized in API 5L and ISO 3183 it is generally regarded as a proprietary product of the group of companies involved in its initial development,

12.10 Material Property Targets

The present review has shown that X100 welded pipe in the SAWL and SAWH product forms can be produced to meet the specified requirements of standards such as ISO 3183, API 5L and CSA Z245-1. [113] The lean composition pipe can be produced with toughness levels that far exceed the minima specified in the above standards and values well above 200J at test temperatures of 0°C or -20°C are typical. A high level of toughness can also be maintained to lower temperatures such as -40°C or even lower. However, verbatim reports of full scale fracture control tests suggests that even this high level of toughness will be insufficient to arrest running fracture in large diameter X100 gas transmission pipelines, necessitating the use of crack-arrestors. Increasing toughness to an even higher level should be an aim, although it is uncertain if a higher toughness target is attainable.

Strain based design and higher design factors such as 0.8 are likely to be used for X100 pipelines for which a fundamental understanding of the tensile behavior of these high strength steels is necessary. Although detailed stress-strain data has been generated, it is held mainly by the pipe producers and the few companies that have used X100 and X120 to date. The standards for these steels allow generally high yield/tensile ratios, although in practice, the actual Y/T values can be somewhat lower. Information on the tensile stress-strain behavior, typical Y/T ratios should be made available in the public domain to assist designers. For strain-based design more information on uniform elongation and longitudinal direction properties must be made available.

In terms of product improvement, reduction of the extent of seam weld HAZ softening and the extent of the HAZ seam weld in the welded pipe is a worthwhile target.

12.11 Technical Approach and Suggested Priorities For Project Development Work

Based on data submissions to this PRCI survey and review it is apparent that a nucleus of pipe mills and user operator companies, with selected contractors have conducted successful development for welding and pipe-lay of L690 (X100) grade line pipe culminating in sections of

X100 being laid into sections of existing gas pipelines in Canada although the trial was essentially a pipe lay welding exercise, rather than a trial in which the full properties of the high strength line pipe were exploited. However, an operational trial simulating long-term operating conditions of an X100 pipeline has been carried out in the UK although full results of that trial have not been published. Combining the experience of these trials indicates that a few companies are well placed to continue with further use of X100. The situation may be similar with the higher strength X120 for which sections have already been welded into a gas pipeline in Canada, but wider publicity about X120 is restricted by proprietary commercial interests.

There is a significant bibliography of conference and journal papers published over the past decade, suggesting that material such as X100 may have been researched more thoroughly than some lower grades of line pipe and industry hearsay suggests that many more tests have been carried out, results of which are not in the public domain. Increasing use of strain-based design suggests that more testing of pipe in the longitudinal direction, possibly by bending or under pressure may have been carried out.

The steel development has taken place over some 15 years or more and, from early pre-production pipe that did not fully meet X100 requirements, current materials meet standards criteria and any improvement will need to be driven by user operator requirements.

A remaining area, for which reliable data and improved toughness is required is that of the toughness requirement to arrest running fracture in large diameter gas pipelines. A small amount of data from some tests has been published but more remains proprietary to the sponsoring companies.

The development of procedures for girth welding was carried out with painstaking thoroughness by Cranfield University and participating companies BP and TCPL with CRC-Evans, Serimer-Dasa and RMS Welding. The procedures have been transferred successfully to the field but it is considered that a large amount of know-how was required for their successful implementation. Notwithstanding this, TCPL managed this technology with pipe-lay contractors who had not been involved directly with the procedure development.

There is some scope for further development of the mechanized GMAW girth welding process to improve productivity and the dual tandem (CAPS) variant merits further use. This may lead to a need to develop new wires to optimize weld properties.

There is scope to develop improved FCAW consumables for tie-in welding.

Finally, it would be perfectly feasible to specify a wish list of trials, tests and/or data provision priorities for a future development project but the genuine priorities can be specified only for a particular project. To attempt to cater for an all-embracing general case would be costly and wasteful as some of the generated data would not be used. The genuine development priorities will be identified by and fine–tuned by each pipeline project on a case-by-case basis.

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