International Symposium on Microalloyed Steels for the Oil and Gas Industry
Edited by W.J. Fazackerley, P. Bordignon, K. Hulka, and F. Siciliano
TMS (The Minerals, Metals & Materials Society), 2007

THE APPLICATION OF X100 TO GAS PIPELINE PROJECTS

Alan Glover[1], Joe Zhou[2], Nobuhisa Suzuki[3] and Nobuyuki Ishikawa[3]

[1]A Glover, Consultant, Calgary, Canada
[2]TransCanada PipeLines, Calgary, Canada
[3]JFE Steel, Tokyo, Japan

Abstract

Traditional pipeline technology will be severely challenged as developments continue in arctic regions. Cost-effective solutions to these challenges can be found through innovative technology and its implementation. TransCanada PipeLines and its partners have been involved in a series of technology programs whose aim is to reduce the cost of Northern pipelines whilst at the same time provide structural assurance and reliability. This paper will describe the overall approach to developing cost-effective solutions utilizing X100 technology and how these programs are interconnected. The topics to be covered will include the approach to the development of X100 pipe technology and its relationship to strain-based design. The paper will describe the integrated approach to limit states design and the key elements affecting strain demand and strain capacities with respect to material engineering and structural engineering, and how TransCanada has been taking advantage of the approach in its implementation of higher strength steels. A prime consideration of the regulatory bodies is the assurance of structural integrity and fracture control plans. The work currently ongoing at TransCanada on fracture safe behaviour will be discussed. The work also includes the approach taken in terms of the design for the effect of mismatch between the pipe and weld metal properties, and recent improvements in mechanized welding. The strain-based approach is also being extended to a structural reliability methodology and the work conducted to date will be briefly discussed. The paper will describe two recent X100 projects that have been designed and constructed in Alberta covering summer and winter approaches, and planned future projects implementing changes to pipe specification to account for strain-based designs.

Introduction

The prime impetus for increasing pressure in a gas pipeline system (and the associated increases in material properties) is economics. On a large diameter pipeline project 25 to 40% of the project cost is related to material, (the variable depends on the location) and hence reducing material costs can have a significant effect on project costs. Many studies [1 - 4] have shown the benefit of using higher strength material and are the driving force for increasing strengths to even higher values. Most of the studies have focussed on the application of X100 although recent work has demonstrated the applicability of X120 [5, 6]. The evolution of these steels is shown in Figure 1, based on studies by Takeuchi [7], which also demonstrates the reduction of uniform strain with increasing pipe yield strength. These higher strength steels however rely on the increasing application of higher pressures, and the trend to higher operating pressures is shown in Figure 2. The application of the higher strength pipeline steels also coincides with a change in the design philosophy from stress-based to strain-based approaches. In which case the relationship between the strain demand and strain capacity has to be taken into account when specifying the material property requirements. In addition the relationship has to also take into account stress-strain behaviour, D/t practicalities, influence of local buckling behaviour and tensile strain behaviour as well as fracture control. This paper will concentrate on the development of X100 for these rigorous requirements, the application of a strain-based design and how this impacts on the material specifications, and the specific application to various X100 projects. The work reported is a combination of the research studies and implementation through joint studies by TransCanada and JFE.

Plate chemistries and manufacturing

Plate manufacturing process has been modified and improved as the demand for higher grade linepipe materials continues to increase. Typical plate and pipe chemistries of present day X100 are shown in Table 1. Thermo-mechanical controlled processing (TMCP) represented by controlled rolling and accelerated cooling process is the essential measure for producing X100 material. Especially, accelerated cooling process plays significant role in balancing high strength and high toughness, as well as good weldability. Plates for X100 linepipes were produced by using "*Super*-OLAC", on-line accelerated cooling device [8]. *Super*-OLAC has achieved ultimate high cooling rate in accelerated cooling process, which gives significant benefit in obtaining high strength and excellent base metal toughness by fine and uniform microstructure. Higher cooling rate also enables reduction of alloying elements resulting in good weldability.

In order to utilize the higher grade linepipe material for the strain-based design application, one of the key issues is how to achieve high deformability of the linepipe in order to achieve high strain capacities for both buckling and girth weld fracture. A great deal of effort has been made to achieve improvement in the deformability of high strength linepipe materials contrary to the general trend of lower elongation of high strength steel (see Figure 1). Multi-phase microstructure controlling techniques were applied for X100 development [9]. Optimized metallurgical design and plate manufacturing conditions utilized by the advanced accelerated cooling facility has enabled significant improvement of deformability even for higher strength materials. The X100 linepipe introduced in this paper achieved sufficiently low longitudinal Y/T ratio with round-house type stress-strain curve while keeping the high strength and toughness for X100 application.

Pipe Material Properties and Strain-based Designs

Strain-based designs may need to address both load-controlled and displacement-controlled scenarios, and need to look at both the circumferential and longitudinal stress-strain properties. In addition, with the use of these X100 yield strength materials, the understanding of how to measure the stress-strain properties appropriately becomes increasingly important. This can be understood by reference to Figure 1, in which it is clear that, other factors being equal, there is a progressive decrease in the useful plasticity of the pipe as the yield strength rises. Since the approach is now to explicitly base design calculations on the strain capacity of the pipe, rather than relying on large but indeterminate reserves of plasticity, this trend is of considerable importance. Additional factors to be considered are the effect of yield to tensile strength ratio (Y/T) on the uniform strain under biaxial loading, and the potential effect of thermal cycles associated with coating operations. Relative to the first of these, both German and Japanese work has indicated that the ratio of uniform strain in vessel tests to that under uniaxial loading decreases rapidly below its theoretical value as Y/T exceeds 0.93 [10]. Australian work has indicated that coating thermal cycles can further reduce uniform strain in vessel tests [11], uniaxial values for uncoated pipe in the low single digits are thus of real concern for strain-based design, even though typical design strains are in the range 1-2%. All aspects of the material properties have been studied as they relate to ordering and performance. The key issues are around manufacturing processes and chemistry, the stress-strain behaviour, yield to tensile ratios (and how to measure these properties), uniform strain, hoop and longitudinal properties, long seam weld properties and toughness requirements.

Measurement of Yield Strength

Pipeline materials have traditionally been specified and qualified using a flattened strap tensile specimen taken in the hoop direction. For the lower strength materials this has provided an adequate representation of the yield strength of the material; in addition the test indicated a low Y/T. In the 70s and 80s, as strength was further increased through the use of controlled processing, and as thicknesses increased to meet increasing diameter and pressure requirements, the adequacy of the flattened strap test was called into question. In the 90s, the issue of strain-based design was beginning to be addressed (see later section), and the relationship between actual properties, in both the hoop and longitudinal directions, and "reserve capacity" became important.

Initial work was commenced on understanding the fundamental behaviour of pipe materials and how to measure not only yield strength but also actual stress-strain behaviour. At increasing strength levels it rapidly became apparent that the flattened strap underestimated the actual yield strength (because of the net effect of strain hardening, Bauschinger effect, and residual stresses), see Figure 3 taken from an EPRG study [12]. The work showed that above X80, the flattened strap significantly underestimated the yield strength of the pipe. Most line pipe standards allow the option of qualifying using either a flattened strap or round bar specimen for higher strength materials. The advantage of using a round bar is that a closer representation of the yield strength is obtained, and the manufacturer does not have to use richer chemical compositions or change the processing route to achieve the nominal yield strength (at a higher cost and/or to the detriment of the overall property package). The disadvantage in some opinions is that a higher yield to tensile ratio is measured, but this is probably a more realistic indication of pipe behaviour. Some recent results from a TransCanada X100 project are given below; the figures shown represent the mean of 27 heats, and show a similar pattern to the EPRG studies. Currently all of TransCanada's specifications for pipe yield strengths greater than Grade 550 require qualification using round bar specimens.

Hoop (transverse)	Yield (MPa)	Tensile (MPa)	Elongation %	Y/T
Round Bar	763	838	21	0.91
Flattened Strap	684	846	27	0.81

As part of the verification of this approach a series of ring expansion tests was performed as part of a Joint Industry Project [13]. The work confirmed that round bar testing for yield strength gave an accurate representation of the pipe material's behaviour. The results obtained on a series of X100 test samples from a range of pipe steel suppliers are summarized below:

Hoop (transverse)	Yield (MPa) Group 1	Yield (MPa) Group 2
Round Bar Avg.	769.7	784.5
Ring Expansion Avg.	771.2	782.0

One aspect of the ring expansion tests on these high-strength steels that did become apparent was some increase in strain localization adjacent to the double submerged arc weld. Currently, joint research programs are underway to investigate this phenomenon further. Initial finite element studies have shown that the relative width of the lower hardness HAZ plays a key role in the strain localization. This factor is also related to the absolute thickness of the material, and is not expected to be an issue for the typical thicknesses required for X100 even at higher design pressures.

These results also highlight the effect of yield to tensile ratio and the impact on uniform elongation. Several studies have been performed on the comparison of behaviour in a circumferential tension test and the corresponding behaviour in a vessel test [14, 15]. These results are summarized in Figure 4. While there is a good deal of scatter in the results it can be seen that the ratio of tensile to vessel behaviour trends to zero at very high Y/T ratios. Using the data from Figure 4 and the results from the present and historical studies the trend line can be expressed in terms of yield strength rather than Y/T. Incorporating the results from the small scale tension tests performed on X70, X80 and X100 pipe steels allows the uniform elongation in a vessel test to be calculated. These results are presented in Figure 5. While it can be argued that the vessel test performance may not be absolutely representative of a pipeline, the trend is clear, in that at the higher yield strengths the uniform strain in the vessel is low. These results need to be further evaluated, particularly as they might apply to the hydrostatic test for high strength steels.

The final issue for the specification of material yield strength relates to the balance between the transverse and longitudinal properties. As discussed in the next section on strain-based design for secondary loads, it is the longitudinal properties that are the key component. For many years TransCanada has been approaching the specification of material properties in the transverse and longitudinal orientation as two distinct requirements. There is no dictate that says the two properties have to be equal, and in fact it may be advantageous to have the two properties unequal, with the longitudinal yield strength being lower. This makes achieving tensile and compressive strain capacity limits much easier, as well as facilitating girth weld overmatching (see below). A typical example from a recent TransCanada project is given below.

	Yield (MPa)	Tensile (MPa)	Elongation %	Y/T
Hoop (transverse)	763	838	21	0.91
Longitudinal	623	801	22.3	0.78

Typical high strength steels undergo complex controlled rolling and cooling processes in order to achieve the required combination of strength, toughness and ductility. The finish rolling temperature is often around the Ar3, followed by some form of on-line accelerated cooling. For the highest strength materials, the stop temperature of the accelerated cooling is often relatively low (in the mid 300 ^{o}C). In general, despite the prevalence of strong carbide- and nitride-formers in these steels, such thermal cycles can leave small but significant quantities of interstitial solutes. Relatively short cycles above 200°C after pipe forming and expansion can then lead to sufficient aging response to influence mechanical properties. A typical time temperature profile for a FBE application is shown in Figure 6. Using this information, several X100 pipe materials were subjected to the same thermal cycle and their stress-strain properties measured after thermal treatment. The results are given below:

Hoop (transverse)	Yield (MPa)	Tensile (MPa)	Uniform Elongation %	Total Elongation %	Y/T
As received	725	803	6.6	19.1	0.9
After thermal treatment	771	811	6.3	18.9	0.95

Longitudinal	Yield (MPa)	Tensile (MPa)	Uniform Elongation %	Total Elongation %	Y/T
As received	615	760	6.1	20	0.81
After thermal treatment	658	773	6.7	18.4	0.85

For these high strength steels it is clear that the coating thermal cycle does have an impact on the yield strength, though inconsistent and limited effects on ductility. This result becomes important when considering tensile strain limits, in particular the desirability of overmatching the weld yield strength to the pipe yield strength in the longitudinal direction over the range of applicable tensile strain limits.

This increase in yield strength effect could also impact on the compressive strain limit, depending on whether the increase is also accompanied by a change in the shape of the stress-strain curve from a roundhouse to one with Luders yielding. In this case the effect would be two-fold; the introduction of Luders yielding would effectively reduce the compressive strain limit and also increase the compressive strain demand. Understanding the influence of the thermal aging on not only the increase in yield but also on the shape of the curve becomes very important. Specifications are now in place to address this particular issue. A secondary factor that is currently under review is the effect of anisotropy on strain capacity and demand.

There are additional factors that may come into play, and this includes the effect of the field cold bending. Investigations are currently underway to determine the extent of this effect; however, the key factor might not be any change in stress-strain behaviour, but rather slight geometry changes as a consequence of otherwise-acceptable and minor wrinkling. These geometric changes can have a significant effect on strain capacity.

Applications

Westpath project and installation of X100

Early in February 2002 a decision was made to implement X100 on one of TransCanada's summer expansion projects, which permitted the installation of 1 km of NPS 48 on the Westpath project. The specific installation of X100 took place on the Alberta Mainline Loop # 2 (Saratoga Section) in Alberta, which consists 20.9 kilometers NPS 48 pipeline X80, and 1.0 kilometers of NPS 48 X100.

The pipe material was supplied by JFE and ordered to the CSA Z245-02 requirements plus TransCanada's internal pipe specification. The internal specification places a much tighter tolerance on the pipe requirements than the CSA code. One of the prime objectives of the project was to gain experience in the manufacturing and construction of X100 so that it could be applied to future high-pressure projects. The specific Saratoga project only required a design of NPS 48 X80 with a wall thickness of 12mm. In order to meet the objectives of the project and to develop longer-term requirements for high-pressure designs it was decided to utilize NPS 48 X100 with a wall thickness of 14.3mm. The design requirements for the pipe were therefore based on that premise. This requirement meant that some rapid development was required at JFE resulting in slight modifications to the U and O procedure and to some of the welding requirements. Nonetheless all of the specification and delivery requirements were met.

One key aspect of the specification of the material was agreement on the type of testing to be performed to verify the material minimum specified yield strength in the hoop direction. Based on the earlier discussion it was agreed to use a round bar for the qualification. At that time CSA did permit use of round bar tensile testing, however the dimensions in the code were not relevant. This issue is being addressed in subsequent code publications. Flattened strap results were, however, collected to add to the database and part of the continuing effort to have code acceptance of the approach. Additional tests were also specified for the longitudinal stress-strain behaviour. These results were for information purposes only but form part of the strain-based design for the tensile strain criteria. All of the results and comparison with the specification are given in Tables 1 and 2.

The results of the chemical analyses show that the pipe met the requirements of TCPL P-04, with a product CE of 0.26, typical of the prior trials. The results of the tensile properties (Table 1) show that the pipe material met the X100 requirements of both CSA and P-04 when qualified with the round bar specimen as specified. The average yield and ultimate were 763 MPa and 838 MPa respectively, with an average Y/T of 0.91 (note that the maximum Y/T was 0.95). As expected the flattened strap results did not meet the requirements in terms of yield of the CSA code, as well the Y/T of these specimens is much lower, again as expected. These results are in agreement with the results published in Figure 3 [12]. The longitudinal properties of the pipe gave slightly lower yield and ultimate, and this was a deliberate action to enable a more efficient strain based design for the tensile strain limits [16]. The pipe weld flattened strap transverse samples all met the CSA and P-04 requirements.

The fracture toughness property requirements of the pipe and weld were determined based on a fracture initiation and propagation control plan. The fracture arrest properties were based on correlations from the full-scale fracture tests and from conventional models with a correction factor [17]. All of the fracture toughness properties (Table 2) met those requirements. Note CSA Z245.1 only addresses nominal pipe body toughness. CSA Z662 (design requirements), addresses the requirements for fracture initiation and arrest design, and for higher pressures and stresses requires a full engineering analysis.

A key requirement for the construction and installation of X100 was the qualification of the various welding procedures. For the mainline this consisted of mechanized gas metal arc procedures and for the tie-ins manual metal arc procedures. The summary of the procedures is as follows

Mechanized Gas Metal Arc Welding (GMAW) with a vertical down welding progression were used for all mainline welds as follows:

- Internal root beads using short circuit metal transfer with 75% Ar - 25% CO_2 shielding gas mixture and 0.9 mm Thyssen K-Nova wire.
- External weld passes using pulsed gas metal arc welding with a 85 %Ar - 15% CO_2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire.

- External cap pass using short circuit metal arc welding with a 85 %Ar - 15% CO_2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire
- 100° C minimum preheat shall be maintained throughout.

Tie-in welds were completed using the shielded metal arc welding (SMAW) process with a vertical down welding progression as follows:

- Root beads completed with E5510-G, minimum preheat 100° C maintained throughout
- Hot, fill and cap passes completed with 4.0 mm Bohler BVD 110 (E11018-G)
- No pipe movement until after completion of the hot pass and there shall be a 24 hour delay prior to inspection for all shielded metal arc welds

All of the welding procedures were qualified by both the contractor and by TransCanada to meet the relevant CSA codes and to be used for both workmanship and alternative acceptance criteria according to Appendix K of CSA Z662-99. Typical results from the procedure qualifications gave the mechanized girth weld with average yield strengths of 698 MPa and ultimate strength of 815 MPa. The respective cross weld tensile tests results all failed in the pipe material and gave corresponding pipe longitudinal properties of yield strength 675 MPa and ultimate strength 811 MPa. Note these longitudinal properties are slightly higher than those reported for the pipe qualification in Table 1 (623 MPa yield and 801 MPa ultimate), however that is not unusual when performing cross weld tests. In either case however the girth weld properties overmatched those of the pipe longitudinal properties and that was one of the main criteria. Additionally prior to the commencement of the project detailed working sessions were held with the contractor and the welders re the welding procedures. This required that an extra welder training school be set up immediately prior to kick off to "re-train" the welders to utilize the pulsed gas metal arc procedures. This was necessary in this particular case because the welders had been on the overall Westpath project all summer constructing the X80 using mechanized short circuit gas metal arc procedures. The change over to the pulsed procedures required some additional training and also requalification. Views of the internal and external welding are given in Figures 3 and 4.

Another potential issue with X100 could have been the field bending. Some preliminary trials had been performed on NPS 36 and also calculations to show that the bending could be performed using a standard CRC bending machine with an internal mandrel. Nonetheless because of the timing of the project and the delivery of the pipe, it was not possible to do any pre-bending trials on the NPS 48 X100 material. Even so the field bending went extremely well. No problems were experienced with the bending, no coating issues arose, the pull times were similar to the X80 project, and slightly shorter pulls were used to compensate for the additional springback. Overall bends of 1 degree per pipe diameter were easily achieved.

Final field installation of X100 took place in late September 2002. After successfully training of the welders all of the welding was completed over a 2-day period. The pipes used for the project were all approximately 12 m in length and no double jointing was performed. The pipes were left as single joints to permit the maximum number of welds to be completed for the relatively short project. All of the pipes were coated using standard fusion bond epoxy coating, with the normal cut back to allow full ultrasonic inspection. All of the field welding and inspection proceeded as planned. Some lack of fusion defects were experienced, however, these were all related to ongoing welder training as opposed to welding process. Weld repair rates were similar to our other start up mainline projects. Final hydrostatic testing of the line was performed in early October and the line was placed in service November 1st 2002 and has been operating since that time without any issues.

Godin Lake project and winter installation of X100

One of the main applications for these high strength steels will be on the emerging northern frontier, where extensive construction will take place in an arctic environment. A second project was therefore approved that allowed for a wide range of winter construction aspects to be evaluated during January and February 2004. TransCanada's Peerless Lake project consists of 17.7 km of NPS 24 X70 in Northern Alberta. The project also included a 3.6 km loop of NPS 36 X100 and X120, known as the Godin Lake loop. The following discussion concentrates on those aspects relating to the installation of the X100; the results of the work on the X120 has been reported separately [5].

The NPS 36 13.2 mm X100 was ordered to the same specification as per the Westpath project, with some modifications and the pipe was supplied by JFE. Again additional testing requirements were included to establish a larger database on the properties of X100. The pipe was ordered to a deliberate policy of slightly lower yield strength in the longitudinal direction to maximize the strain base design approach (Table 3). Additional work on the tensile and compressive strain behaviour of the material was subject of a separate r and D program and the results are presented in a paper by Sadasue et al [18]. The results of the yield and tensile properties also confirm the previous analyses on qualification using the round bar specimens and the results fall in line with the results shown in Figure 3. This approach was further confirmed with some limited ring expansion tests, which showed that good agreement was obtained between the round bar results and ring expansion results. The toughness test results are given in Table, which all exceeded the specified requirements. The requirements were based on the previous Battelle 2-curve approach, modified based on the results from a series of full-scale fracture tests on X100.

An extensive amount of welding development occurred prior to the Godin Lake project. The welding development had two main thrusts. The first was to modify slightly the single wire pulsed procedure that was utilized on the Westpath project. The aim of the modification was to eliminate the minor imperfections that were occurring in the hot pass/first fill region. This was achieved and the procedure fully qualified for the use on Godin Lake. The second major thrust was to implement higher productivity pulsed tandem welding, and this was a key objective for the project. TransCanada together with BP and Cranfield University have been working on high productivity tandem welding for several years. This has included both single tandem and dual tandem welding. The tandem process essentially relies on having 2 wires through one head, single tandem consisting of only one head and dual tandem consisting of 2 heads. While both procedures were ultimately qualified for the project only the single tandem was ready in time to meet contractual timelines. The final procedure qualified and used on the project was a "hybrid" combination of single wire pulsed and single tandem pulsed as follows:

Mainline:

- Internal root beads using short circuit metal transfer with 75% Ar - 25% CO_2 shielding gas mixture and 0.9 mm Thyssen K-Nova wire.
- External hot and first fill weld passes using pulsed gas metal arc welding with a 85 %Ar - 15% CO^2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire.
- External 2nd and 3rd fill and cap pass using pulsed gas metal arc single tandem (2 wires) with a 85 %Ar - 15% CO_2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire, Cranfield automated pipewelding system with Fronius Digital power sources for tandem welding
- 100° C minimum preheat shall be maintained throughout.

Tie-in procedures as per Westpath. Note subsequent to this project a mechanized flux cored tie in procedure has been developed and validated and will be implemented on the next project

The project was welded in extreme winter conditions with temperatures as low as -45°C and no issues with the constructability of X100 were experience. All welds were inspected using 100% mechanized ultrasonics and accepted using an Engineering Critical Assessment as per Annex K of CSA Z662-03. The welding of the X100 using the hybrid procedure went extremely well and very low repair rates were achieved (Figure 8). Positive feedback was received from the welding crews and no issues arose from using the high productivity processes. The next stage will to implement both the full single tandem and ultimately the dual tandem.

A continuing development on high strength projects is the development and application of high strength fittings. The complexity of the Godin Lake project with both X100 and X120 being utilized, and the very tight right of way corridor, provided the opportunity to implement Y80 fittings. Five 3R 26-28 degree fittings were installed (Figure 9) which had a similar chemistry to pipe but higher microalloy content and were quenched and tempered. Typical mechanical properties were Yield Stress 611 MPa, Tensile Stress 693 MPa, and Elong. 22% Charpy at -45°C, Fitting 58J, Weld 87J (design was on fracture initiation requirement only). These high strength fittings were the first to be installed worldwide. Work continues on the development of a wide range of high strength components and it is expected that these will be available for the next project.

Normal installation of the pipeline took place in March 2004 (Figure 10), and no difficulties were experienced with the laying of the X100 and only one additional side boom was utilized. Normal cathodic protection design was employed for this pipeline and no issues have arisen since the pipeline went into full operation in March 2004.

Next project 2006

The next installation of X100 is planned for the summer of 2006. On this project it is planned to install approximately 5.5 km of NPS 42 pipe as part of a larger X80 project. Although this project is a nominal "stress-based" design, the X100 material has been ordered to a full strain-based design, and has incorporated all of the thinking and advancements over the previous two projects. The prime changes relate to the specification for the material. Steel chemistries and manufacturing processes are staying somewhat the same but the emphasis has been on the stress-strain characteristics in both the hoop and axial direction, and specifically the shape of the stress-strain curve. In the strain-based design it is important to consider the effect of Luders yielding on both the strain demand and the strain capacity, particularly for the buckling component. The presence of Luders yielding increases the strain demand and reduces the strain capacity. It is particularly important therefore to understand the behaviour of the steel in not only the as-received condition but also in the thermally aged, and/or cold bent condition. Specifications therefore have been developed that require "round-house" behaviour in the as-received and thermally aged conditions. These have been achieved. In addition steelmakers are addressing the issue of low temperature aging through their manufacturing process, and this combined with the effort of the coating manufacturers to also produce a low temperature cure product will also be beneficial. While understanding stress-strain properties is important from a compressive strain capacity aspect, it is also important from a tensile strain requirement. Though the shape of the curve in this case is less important the requirement to overmatch the weld metal strength over the range of strain demand is particularly important to achieve reasonable strain limits. Weld procedures have been developed that incorporate single tandem processes that will achieve the requisite level of overmatching. This aspect is particularly important with respect to tensile strain limits as they represent ultimate limit states as compared to the serviceability limit state of the onset of buckling. Finally the design has incorporated a fracture plan that is based on self arrest, utilizing a conventional Battelle 2-curve approach with a correction of 1.7 to 2.0. Self arrest can be achieved because of the lower design factor, however future projects will require a crack arrestor approach at higher design factors.

Summary

Economic pressures will ensure that challenges in pipeline applications will continue to be met though the use of innovative design approaches, which incorporate high strength pipeline steels including X100. It has been shown that these technologies can provide safe and reliable systems whilst at the same time enabling cost-effective solutions. The use of higher strength pipeline materials, alternative pipeline materials, innovative designs including strain and reliability-based approaches, structural integrity solutions and alternative construction technologies are all contributing to the ability to meet these challenges. Nevertheless, the use of some of these methods makes much greater demands on our understanding of the applicable mechanical properties under realistic loading conditions and stress states. Traditional pipeline design hardly addressed these issues at all, but relied on the inherently large reserves of plasticity characteristic of lower strength materials. Pipeline materials being applied today can have levels of uniform strain that are not many times higher than are needed for design. This situation puts a premium on realistic and accurate determination of properties, and also makes it essential, when developing new materials and production routes, to consider the entire package of mechanical properties that will be required. Two projects utilizing X100 have demonstrated this capability. A third project incorporating a fully strain-based design approach for X100 materials has been designed and is intended for application in 2006. These projects have demonstrated that X100 is ready for application to major projects and can deliver the benefits that will enable the projects to be economically viable.

References

1 Glover A., “Application of Grade 550 and 690 in Arctic Climates”, Proc. Of Application & Evaluation of High Grade Linepipe in Hostile Environments Conf., Nov 2002, Yokohama
2 Barsanti L., Bruschi, R., and Donati, E., “From X80 to X100: Know-how reached by ENI Group on High Strength Steel” Proc. Of Application & Evaluation of High Grade Linepipe in Hostile Environments Conf., Nov 2002, Yokohama
3. Fairchild et al. “High strength steels-beyond X80” Proc. Of Application & Evaluation of High Grade Linepipe in Hostile Environments Conf., Nov 2002, Yokohama
4 Petersen, C. W, Corbett, K. T., Fairchild, D. P., Papka, S. D., Macia, M. L., "Improving Long Distance Gas Transmission Economics-X120 Development Overview," Proc 4th Int'l Pipeline Technology Conf, Ostend, Belgium, May 9-13, 2004,
5. Papka, S. D., Stevens, J. H., Macia, M. L., Fairchild, D. P., Petersen, C. W., "Full-Size Testing and Analysis of X120 Linepipe" Oil & Gas J., Vol. 102. 8
6. Asahi, H., Hara, T., Tsuru, E., Terada, Y., Sugiyama, M., Maruyama, N., Morimoto, H., Shinada, K., Koyama, K., Murata, M., Doi, N., Miyazaki, H., Yoshida, T., Ayukawa, N., Akasaki, H., 2004, "Metallurgical Design of High Strength Steels and Development of X120 UOE Linepipe", Proc 4th Int'l Pipeline Technology Conf, Ostend, Belgium, May 9-13, 2004

7. Takeuchi, I., Fujino, J., Yamamoto, A., and Okaguchi, S., "The prospect of high-grade steel pipe for gas pipelines" Proc. Of Application & Evaluation of High Grade Linepipe in Hostile Environments Conf., Nov 2002, Yokohama
8. Endo, S., Ishikawa, N., Kondo, J., Suzuki, N. and Omata, K., "Advance in high performance linepipes with respect to strength and deformability" Proc. Of Application & Evaluation of High Grade Linepipe in Hostile Environments Conf., Nov 2002, Yokohama
9. Okatsu, M., Shinmiya, T., Ishikawa, N., Endo, S. and Kondo, J., "Development of high strength linepipe with excellent deformability", Proceedings of OMAE 2005, June 2005, Halkidiki Greece.
10 Gaessler, H. and Vogt, G. (1989), "Influence of Yield to Tensile Ratio on the Safety of Pipelines". 3R International.
11 Fletcher L. (2003) personal communication.
12 Knauf G. and Spiekout J. (2002), 3R International Special Edition 13/2002.
13 Millwood N.A., Morgan G. C., Wood A. M., and Batte A. D., "The Influence of Tensile testing Method on the measured Properties of High-Strength Steel Linepipe" 4th International Pipeline Technology Conf. Ostend May 2004
14 Gaessler, H. and Vogt, G. "Influence of yield to tensile ratio on the safety of pipelines", 3R International, H. 3, 1989
15 Knauf, G. and Vogt, G., "Safety in long-distance gas and oil transmission pipelines", 3R International 5, 2001
16 Zhou, J., and Glover, A., G., "Strain based design of pipelines – The path forward" Proc of RIO Pipeline 2005, October
17 Demonfonti, G., Mannucci, G., Harris, D., Barsanti, L., and Hillenbrand, H-G., "Fracture behaviour of X100 gas pipeline by full-scale tests" Proc. Of Application & Evaluation of High Grade Linepipe in Hostile Environments Conf., Nov 2002, Yokohama
18 Sadasue, T., Igi, S., Kubo, T., Ishikawa, N., and Endo, S., "Ductile Cracking Evaluation of X80/X100 High Strength Linepipes" Proc of IPC 2004, Calgary, Oct 2004

Table 1. Chemistries for X100 Westpath Project

Spec & Heat No. For Grade 690 Production	JFE Mfg. No.	Type of Analysis	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Nb	V	V + Nb	Ti
CSA Z245.1-02 (Heat & product)			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 P-04 & TA #2, Rev. 0 (Heat & product)			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
3-7046	27-00399	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
3-7046	27-00399	Product	0,05	0,09	1,87	0,009	0,001	0,28	0,13	0,03	0,21	0,04	0,00	0,04	0,008
3-7701	27-00435	Ladle	0,06	0,12	1,86	0,009	0,001	0,25	0,15	0,03	0,21	0,04	0,00	0,04	0,010
3-7701	27-00435	Product	0,06	0,11	1,87	0,009	0,001	0,26	0,13	0,03	0,20	0,04	0,00	0,04	0,010
3-7705	27-00447	Ladle	0,06	0,11	1,84	0,008	0,001	0,26	0,14	0,04	0,22	0,04	0,00	0,04	0,012
3-7705	27-00447	Product	0,06	0,11	1,86	0,008	0,001	0,27	0,13	0,04	0,22	0,04	0,00	0,04	0,012

Table 2. Tensile Properties from X100Westpath project (September 2002)

	Tensile Properties Westpath Project											
	Pipe Body - Transverse								Pipe body - Longitudinal Round Bar Specimens			
	Flattened Strap Specimens				Round Bar Specimens							
	YS MPa	TS MPa	EL %	Y/T Ratio	YS MPa	TS MPa	EL %	Y/T Ratio	YS MPa	TS MPa	EL %	Y/T Ratio
CSA Z245.1-02	690 825	760 970	Min 17	Max. 0,93	690 825	760 970	Min 11	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

Table 3. Toughness Properties from X100 Westpath Project

	Pipe Body, Weld, and Heat Affected Zone Toughness – Transverse Specimens Westpath Project						
	Charpy Impact Tests @ -5°C				Drop Weight Tear Tests @ -5°C		
	Body any heat (J)	Body AHA (J)	Weld (J)	HAZ. (J)	Energy (J)	Shear any heat (%)	Shear AHA (%)
CSA Z245.1-02	40		NS	NS	NS	50	85
TCPL	140	210	75	75	NS	85	90
Average	241		112	122	7781	100	
Minimum	214		98	94	7059	100	
All Heat Average		241					100

Table 4 Tensile properties from X100 Godin Lake

	Tensile Properties Godin Lake Project							
	Transverse				Longitudinal			
	YS	TS	Elon.	Y/T	YS	TS	Elon.	Y/T
	MPa	MPa	%		MPa	MPa	%	
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
Standard Dev.	28,3	36,6	1,8	0,00	20	31,2	1,3	0,03
No. of Samples	24	24	24	24	24	24	24	24

Table 5 Toughness Properties from X100 Godin Lake Project

Godin X100		Charpy Tests @-5°C; Joules			DWTT @-5°C (pressed notch)	
All Samples		Body	Weld	HAZ	Energy	% Shear
Minimum		125	90	69	5394	98
Average		236	118	103	6425	100
Maximum		302	152	173	7811	100
Standard Dev.		34.7	16.3	25.1	638.7	0.4
No. of Samples		24	24	24	24	24

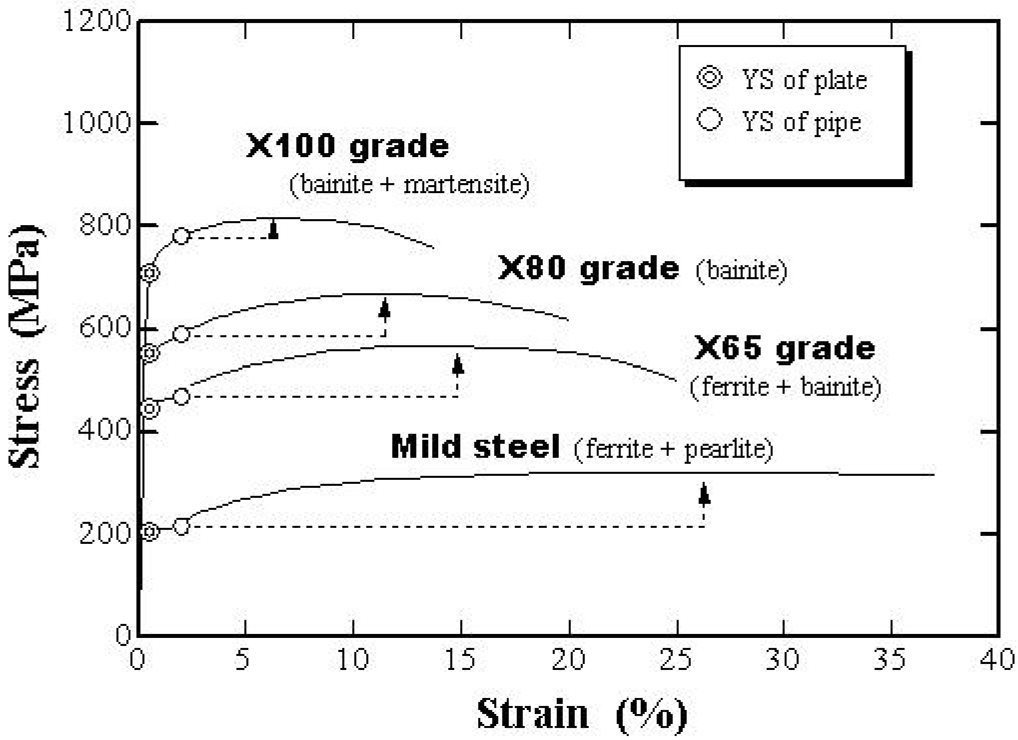

Figure 1. Stress-strain behaviour of pipe materials at increasing strength levels (after Takeuchi [7])

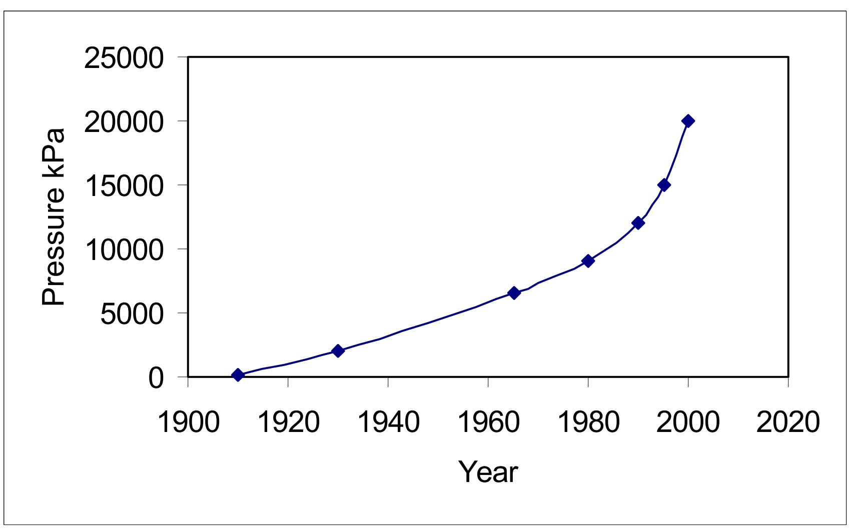

Figure 2. Trend in changing system-operating pressures

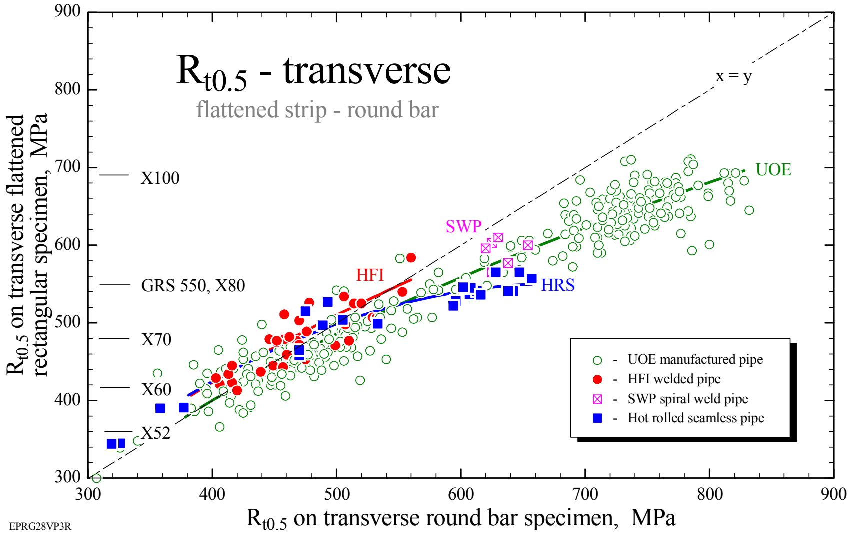

Figure 3. Comparison of yield strengths as measured by flattened strap and round bar for different pipe types (After G. Knauf and J. Spiekout, [12])

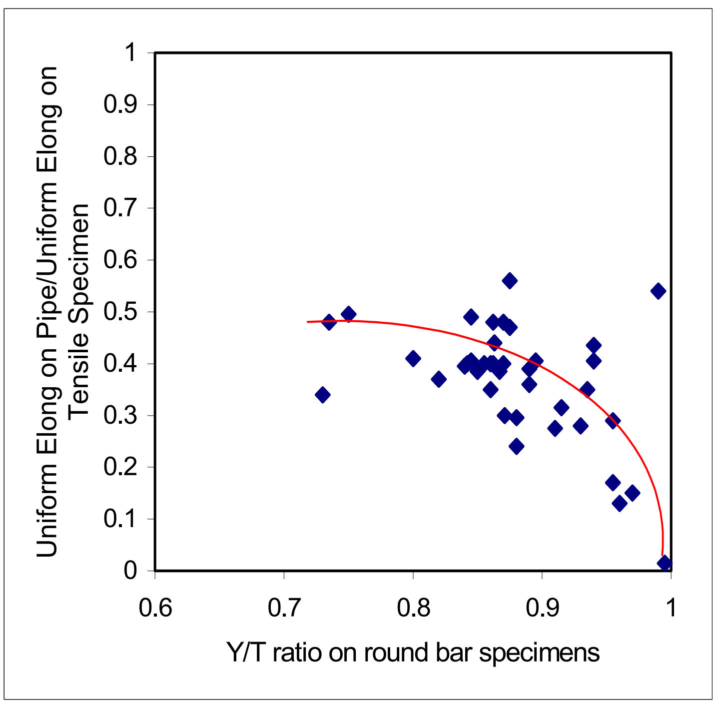

Figure 4. Comparison of various data on effect of Y/T on ratio of uniform elongation in tension test to vessel test. (after 14, 15)

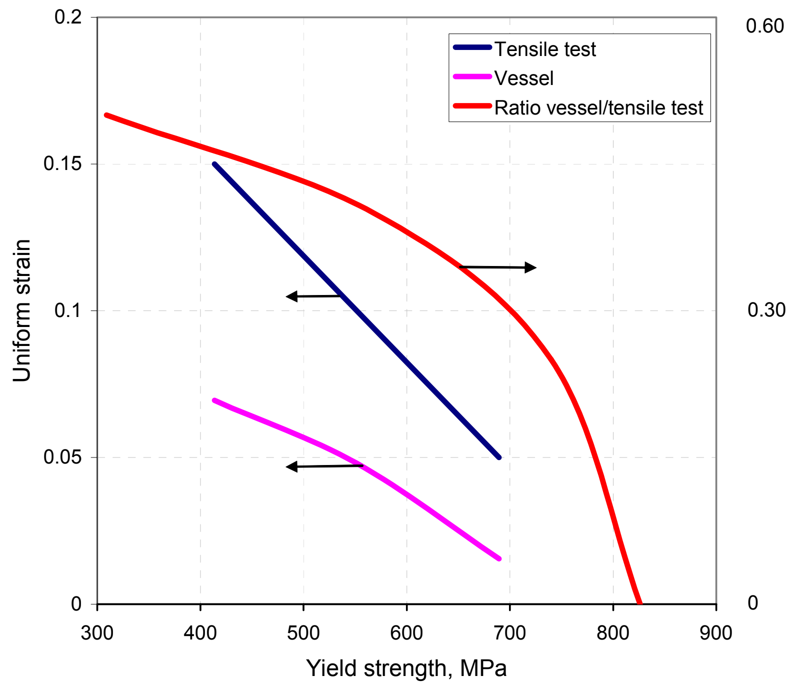

Figure 5. Calculated uniform strain in a vessel test, based on measured uniform strain in a tensile test and approximate ratio deduced from Figure 4**.**

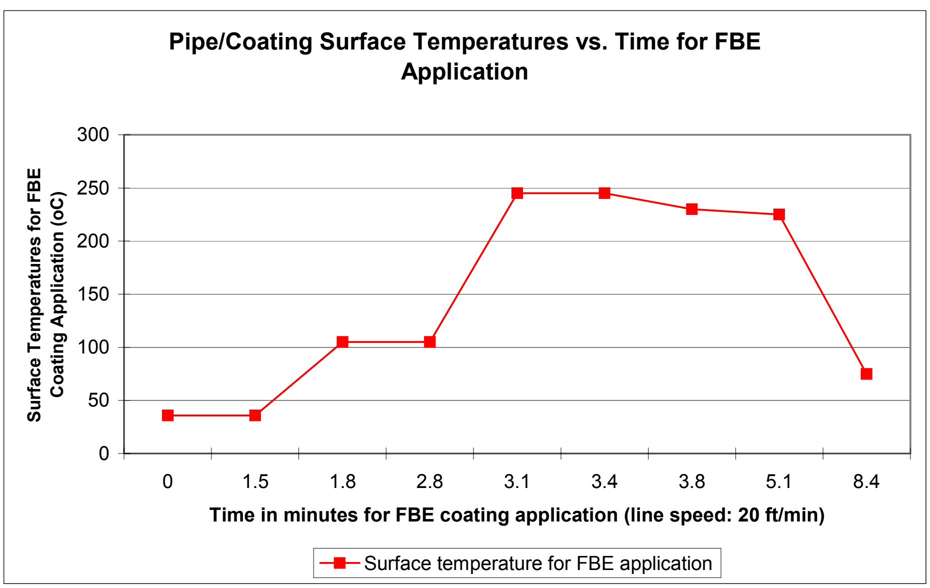

Figure 6. Thermal cycle for application of fusion bond epoxy coating

Figure 7. Winter construction of Godin Lake X100 project

Figure 8. Application of single tandem on welding X100 Godin Lake

Figure 9. First application of Y80 fittings on Godin Lake project

Figure 10. Lowering-in of X100 on Godin Lake