PIPELINE DESIGN AND CONSTRUCTION USING HIGH STRENGTH STEELS

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Keywords: High Strength Pipeline Steels, Design, Welding

Abstract

As the demand for natural gas as a prime global energy source continues to grow, the search for new sources of the fuel spreads into geographical areas that are more remote from the marketplace. Along with this comes the need for longer and ever more efficient pipelines. This requirement for higher value in natural gas transportation is satisfied to a large extent through the application of high strength pipeline steel technology and innovative design approaches that support increased design and operating pressures. This paper reviews the latest accomplishments and successes in these technologies for use in gas transmission. The paper will focus on the application of Gr. 555 (X80) and Gr. 690 (X100) steel technology, the application of stress-based and strain-based designs and the implications of these technologies in terms of the approach with respect to construction welding technologies. It also explores some of the technologies which are targeted for the future to allow the industry to achieve even higher benchmarks in reliability and cost-effectiveness.

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 variation 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 this is the driving force for increasing strengths to even higher values. Most of the studies have focussed on the application of Gr. 555 and Gr. 690 although some studies have shown a specific applicability of Gr. 830 [5, 6]. The evolution of these steels is shown in Figures 1 and 2, based on studies by Gray [5] and Takeuchi [6], the latter figure also demonstrates the reduction of uniform strain with increasing pipe yield strength. The approach to these higher strength pipeline steels has been to utilize the complex microalloying and thermomechanical treatment route, often relying on the C-Mn-Nb chemistries. The use of these higher strength steels however also relies on the increasing application of higher pressures, and the trend to higher pipeline operating pressures [1]. 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 this 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 Grades 555 and 690 for these rigorous requirements, the application of a stress- and strain-based design and how this impacts on the material specifications and welding practices, and on some specific applications to high strength pipeline projects.

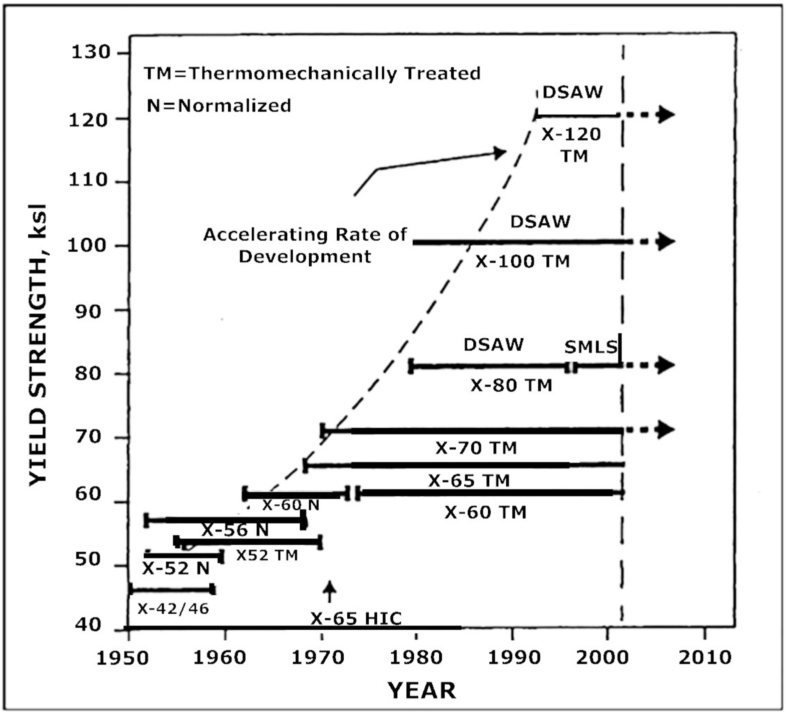

Figure 1. Development and application of pipe grades after J. M. Gray [5].

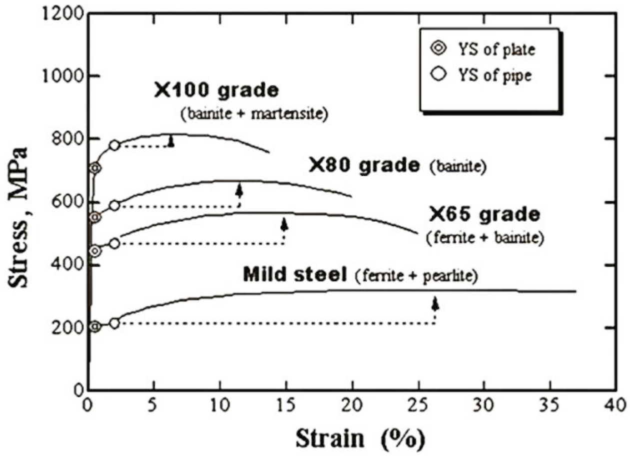

Figure 2. Reduction of uniform strain as pipe grade increases adapted from Takeuchi [6].

Material Design

Allowable Stress Design

Traditional design has been performed using the Allowable Stress Design (ASD) approach which:

- Uses a single, global safety factor, and typically limits the design to some factor of the yield stress (depending on the location).
- Deals with uncertainty through the use of the global safety factor(s), which are semi-arbitrary values based on experience and a qualitative estimate of the risk of failure (primarily pressure).
- Uses a Nominal Strength $\geq$ Sum of Nominal Load Effects.
- Incorporates a Safety Factor.
- Is safe and conservative BUT only considers pressure as a failure mechanism.

Typically the design is optimized based on required flow and delivery requirements and the simplified Barlow's Formula is used to relate the pressure, wall thickness and Specified Minimum Yield Strength incorporating the appropriate location factor [7]. The appropriate Code then specifies the minimum requirements in terms of yield and tensile strengths applicable to the design. However, these are the minimum requirements and often there are specific project designs that require that those Code requirements be supplemented, e.g. specific requirements on the yield and tensile ranges, specific requirements on the Y/T ratios, specific requirements on chemistry, specific requirements on toughness etc. In which case the supplementary requirements are identified and are in addition to the minimum Code requirements on the pipe specification and procurement.

The pipe wall thickness selected shall provide adequate strength to prevent excessive deformation and collapse taking into consideration mechanical properties, permissible variations in wall thickness, ovality, bending stresses, and external reactions. Generally the stress design requirements in the Standards are considered to be adequate under conditions usually encountered and for the general stress design of conventional pipeline systems. Additional requirements may be required when considering displacement loadings etc.

- For straight pipe the design pressure for a given wall thickness or design wall thickness for a given design pressure is determined by the following design formula:

$$P = \frac{2St}{D} \times AF \times J \times T$$

Where:
P = Design pressure MPa
S = Specified Minimum Yield Strength MPa, as specified in the applicable pipe standard or specification
t = Design wall thickness mm
D = Outside diameter of pipe, mm
AF = F in the US (design factor)
AF = F x L in Canada where F is the design factor (normally 0.8) and L = Location factor (depends on Class)
J = Joint factor (typically 1 for submerged arc welded pipe)
T = Temperature factor (typically 1 for temperatures up to 120^{o}C)

Allowable Strain Design

Increasingly for newer projects and developments in challenging areas the pipeline design has to take into account the situation where axial displacement-controlled loads are a factor in the pipeline response [8]. The approach is described in the following section:

- Used for a pipeline design in challenging environments such as active seismic areas, areas of ground instability, areas of slope instability, permafrost regions etc.
- The same design checks would be performed for the calculation of the transverse properties for the Allowable Stress Design to ensure that the applicable Code requirements are met.
- Focus now is on failure modes, during operation, particularly tensile and compressive strain capacities such that:

  Strain Capacity > Strain Demand
- Line pipe material focus is now on longitudinal pipe properties and overall stress-strain behaviour.

Two design checks are now made in terms of the line pipe properties. The first is identical to the design check for the conventional line pipe described previously and all the same limitations apply to the transverse properties as well as the fracture control properties. The second design check now addresses the requirement that the strain capacity exceeds the calculated strain demand. This aspect primarily focuses on the tensile and compressive strain capacities and these relate primarily to the longitudinal pipe properties (which are not normally addressed in the pipeline standards). The longitudinal properties do not have to be the same as the transverse properties and there are advantages to them being lower than the transverse.

The tensile strain capacity is primarily controlled by the field girth weld properties and particularly achieving overmatching of the longitudinal pipe properties for both the yield and tensile values. Achieving overmatching is facilitated by lowering the minimum yield and tensile strength of the pipe and also restricting the range of those properties. Hence the approach is to specify the transverse properties based on achieving minimum Code requirements as well as project specific requirements and to specify the longitudinal properties based on achieving overmatching by reducing slightly the values from the transverse values.

In addition because this approach addresses failure mechanisms it is important to understand the properties in the operating condition, hence the effect of coating on thermal aging must also be assessed. The compressive strain capacity is a function of the peak moment yield and hence is a function of the local behaviour at yield and results in the assessment of the shape of the stress-strain curve in both the as-received and thermally aged conditions. The uniform elongation is also an important consideration for limit state assessment and becomes an additional assessment of the longitudinal properties. Typically longitudinal properties are not a Code requirement hence their specification becomes a supplementary requirement for the pipe.

Not only are the tensile properties of the pipe important but also the HAZ properties of the field weld are important in terms of understanding the overall behaviour. Hence the pipe chemistry is specified to try and minimize any large amounts of HAZ softening as a function of weld heat input. This also controls the HAZ toughness of the field weld and the toughness requirement is set at a minimum specified Charpy toughness and possibly CTOD and SENT values.

In terms of the compressive capacity, as this is controlled by peak moment yielding, there needs to be consideration of the shape of the stress-strain curve. A round-house behaviour is desirable (and this also helps the tensile strain capacity), and some limits need to be assessed on the actual shape at and around yield. This can be achieved by addressing the stress ratio (ratio of stress to strain from the stress-strain curve) at fixed strain levels. The specific values will depend on the design demand and capacity requirements, and the properties of the pipe during operation (i.e. understand the effect of coating on thermal aging behaviour and cold bending on stress-strain properties).

The material design must also consider the achievement of minimum properties to meet the fracture control and mechanical damage requirements.

In the case of tensile strain capacity the key inputs are the overmatching of the field weld properties compared to the longitudinal pipe properties and the local weldment properties [8]. Originally overmatching at yield was considered important [9]; however the present day approach is to consider overmatching over the range of the stress-strain curve and primarily to focus on overmatching at ultimate. Hence it is important to know the range of the longitudinal yield stress and the range of the longitudinal tensile stress, so that the appropriate range of field weld properties can be specified to achieve the required tensile strain capacity. These longitudinal properties need not be the same as the transverse properties and in fact it is beneficial to reduce the longitudinal properties of the pipe compared to the transverse properties and also to restrict the range of the properties. In addition, to meet the tensile strain capacity requirements, it is also important to assess the uniform longitudinal elongation and this value decreases as the pipe yield strength increases (Figure 2 for illustrative purposes).

In the case of compressive strain capacity the key inputs are the longitudinal stress-strain behaviour at peak moment, the shape of the stress-strain curve and also the geometry of the pipe (both D/t and shape). Knowledge of the compressive yield stress behaviour can also be utilized in the modelling of compressive strain capacity; however this can be assessed from knowledge of the transverse and longitudinal tensile stress-strain behaviour. From a design perspective D/t is essentially controlled by the pressure design in the transverse orientation and hence the focus tends to be on the shape of the stress-strain curve and geometric shape control.

In setting the requirements for the longitudinal mechanical properties these are initially functions of the transverse properties. The transverse properties are controlled by the pressure containment requirements whereas the longitudinal properties are controlled by the failure criteria (capacity) requirements. A reduction in the longitudinal tensile properties compared to the transverse properties aids in the achievement of overmatching of the field weld [8], but the reduction must be balanced by the biaxial loading behaviour. The pipe design, strain demand and operating conditions will influence the reductions required in the tensile stress ranges to achieve this balance.

Materials

Pipelines are increasingly being designed using a strain-based approach for secondary loads, and formal reliability-based approaches are being developed. These methods address the strength requirements in terms of specific limit states (tensile or compressive), and a rational approach to target reliabilities based on the consequences of exceeding them. Historical stress-based approaches focused mainly on the hoop stress and its relationship to the specified minimum yield strength. No particular attention was paid to the post-yield stress-strain behaviour of the material. The application of these alternative design approaches, together with the use of higher strength pipeline steels, have shifted that focus and yield and early plasticity behaviour become critical factors.

Concerns over the measurement of yield strength and the relationship of the mechanical properties measured on small specimens to structural behaviour are not new phenomena. Over thirty-five years ago, it was realized that more sophisticated approaches to the metallurgical design of structural and pipeline steels could yield enormous benefits in terms of the overall package of strength, fracture resistance and weldability that could be economically achieved [10]. However, these developments (in particular, an emphasis on low carbon content, fine grain size and precipitation strengthening) increased yield strength much more than tensile strength. At the time, designs based on yield strength were not common in structural engineering, though they were for pipelines. In all cases, however, the perception of a decreased margin between initial yielding and structural failure placed an increased emphasis on the accurate and realistic determination of yield strength [10]. In addition, questions were raised concerning the importance of strain hardening behaviour [11].

Despite these early concerns, the relatively low strength pipeline materials in use at the time had ample reserves of plasticity. In the traditional, reference stress design approach, no specific attention was paid to the stress-strain properties of the material. Rather, the approach was to limit the hoop stress through a series of factors intended to ensure that the pipe was operating comfortably below its specified minimum yield strength. Some thought was given to the possibility that pipes could yield during hydrostatic testing, but this was addressed only by arbitrary limits on volume strain. For low-strength steels, this approach was conservative and worked well. Pipes could be qualified using flattened strap tensile tests, yield to tensile ratios tended to be low, and the possibility that tensile properties in the longitudinal direction could be different was generally ignored without adverse consequences.

Strain-based designs 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 significantly higher 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 2, 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 design calculations are now based 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 [12]. Australian work has indicated that coating thermal cycles can further reduce uniform strain in vessel tests [13]; 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 1-3%. Recent work by steelmakers and pipe makers, however has taken these factors into account and great improvements have been made in the performance of high strength pipe materials [14].

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 1970s 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 1990s, the issue of strain-based design was beginning to be addressed, 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), Figure 3 taken from an EPRG study [15].

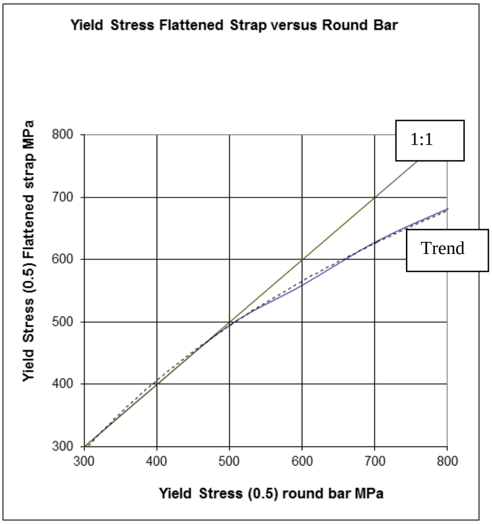

Figure 3. Comparison between flattened strap and round bar yield stress.

The work showed that at about Gr. 555, the flattened strap began to significantly underestimate 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 better 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 Gr. 690 project are given in Table I; the figures shown represent the mean of 27 heats, and show a similar pattern to the EPRG studies.

Table I. Comparison of Flattened Strap to Round Bar for Gr. 690

Hoop (Transverse)	Yield (MPa)	Tensile (MPa)	Elongation %	Y/T
Round Bar	763	836	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. 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 Gr. 690 test samples from a range of pipe steel suppliers are summarized in Table II:

Table II. Comparison of Round Bar to Ring Expansion Tests

Hoop (Transverse)	Yield (MPa) Group 1	Yield (MPa) Group 2
Round Bar Avg.	769.7	784.2
Ring Expansion Avg.	771.2	782.0

The trend today for strain-based designs is to approach the specification of material properties in the transverse and longitudinal orientations 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. The balance between the two properties also is important when considering the biaxial loading of a pressurized pipeline. A typical example of actual properties from a recent high strength project is given in Table III.

Table III. Comparison of Transverse and Longitudinal Properties for Gr. 690

	Yield (MPa)	Tensile (MPa)	Elongation %	Y/T
Transverse round bar	763	838	21.0	0.91
Longitudinal strap	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 °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 150 °C after pipe forming and expansion can then lead to sufficient thermal aging response to influence mechanical properties. Typical coating time temperature profiles for a FBE and 3-layer coating application showed that peak temperatures could be between 210 and 240 °C for short cycles. The steelmakers now take this approach into account in the development of their microalloyed steels and the respective thermomechanical treatment [14] such that previous challenges with marked increases in yield strength have been eliminated (only Bauschinger effects remain) and at the same time eliminating the propensity to Luder's Yielding when thermally aged. In this case the complex interrelationship with carbon and microalloy chemistry and thermal treatment becomes important.

Construction

Standard construction technology has been applied successfully to all high strength pipeline projects. In the first project (Ruhrgas, [16]) that was constructed using Gr. 555, standard shielded metal arc welding processes were applied using low hydrogen consumables. This particular project did not involve high productivity requirements and was primarily concerned with the development and application of Gr. 555 pipe. Rapidly as Gr. 555 became established as a pipeline material the welding processes changed to mechanized welding procedures. From the mid 1990s onwards initially standard GMAW mechanized welding procedures were applied [17] and ultimately pulsed GMAW procedures were utilized to give optimum welding properties [18].

The use of Gr. 555, (Gr. 550 CSA designation at that time) was introduced by TransCanada in 1995 and marked the first use in North America of this technology, which has since been used extensively worldwide on subsequent large diameter projects. This application also led to the introduction of innovative mechanized gas metal arc welding processes as well as the understanding of pipe/weld mismatch properties for strain-based designs. In 1999, following extensive R&D work by TransCanada and various pipe mills, Gr. 690 was first applied. Several trial projects have been implemented to gain experience in manufacturing and installing this high strength steel, albeit typically with a Gr. 550 design approach. These trials permitted the development of high strength single tandem and dual tandem weld approaches and also high strength fittings which are applicable to both Gr. 555 and Gr. 690.

This progressive development and application of high strength pipe steels established the detailed requirements for, and relation between, pipe chemistry, microstructure and mechanical properties of thermomechanically treated line pipe to be fully understood. In addition it heralded an era of collaborative studies with various pipe mills, universities and research organizations to better understand pipe behaviour for strain-based designs, as well as to understand weld mechanics and mismatch effects. These studies also helped establish the ability to relate the behaviour of small-scale test coupons to full-scale pipes. Additionally, the effect of anisotropy on stress-based and strain-based designs was addressed. The work also permitted the understanding of full scale fracture behaviour for these high strength steels and permitted fracture control plans to be developed [19]. The programs accelerated in 1999 when renewed interest in the Alaska and Mackenzie Delta projects emerged. As a result of a series of internal projects and collaborative projects with pipe mills and other pipeline companies, Gr. 690 was successfully implemented on the Westpath project in the fall of 2002. These initial programs also allowed innovative joining technologies to be developed. The emphasis leading up to the first project was on developing mainline mechanized girth welding procedures and manual tie-in procedures. The joining technology has also focused on developing procedures that would meet strain-based design for frost heave and for severe winter service. Procedures have been developed for mechanized welding using pulsed GMAW using standard wires and various gas mixtures. Developments included higher productivity applications (twin wire, twin torch). A low hydrogen vertical down manual metal arc procedure or a vertical up flux cored procedure was also developed for tie-in welds. The initial project application led to continuing development on higher productivity process/procedure and tie-in procedures. In addition the work developed the basis for the current curved wide plate test protocols for strain-based designs.

The first installation of Gr. 690 took place on the Saratoga loop in Alberta, which consisted of NPS 48 Gr. 550 12 mm wall, where 1km of the Gr. 550 pipe was replaced with Gr. 690. In order to meet the objectives of the project and to develop longer-term requirements for high-pressure designs, it was decided to utilize Gr. 690 with a wall thickness of 14.3 mm. This wall thickness was based on preliminary trials that indicated it to be the minimum attainable at that time (note the longer term plan was for thicker wall) and also represented a compromise with respect to the project wall thickness. The pipe material was supplied by JFE and ordered to the CSA Z245-02 requirements plus TransCanada's internal P-04 specification [1]. One of the primary objectives of the project was to gain experience in the manufacturing and construction of Gr. 690 so that it could be applied to future high-pressure projects. The design was purely stress-based and intended for summer construction.

No issues were experienced with handling the pipe, standard practice was utilized without any problems. In order to evaluate the bending of the Gr. 690 pipe, a series of comparisons was performed against the NPS 48 12 mm thick Gr. 555 line pipe. The bending machine was a standard CRC 48 inch mandrel and the bend angles were from 1 to 8 degrees. For all of the field bends no problems arose, no wrinkles were observed and no coating damage occurred. No measurable changes in wall thickness or coating thickness occurred as a result of the field cold bends for both materials. The main difference was that for the Gr. 690 slightly more pulls were required for the same ultimate bend angle. This was to be expected as the springback for the Gr. 690 was slightly more than the Gr. 555 and hence slightly shorter pull lengths were utilized. Nonetheless the overall time for each of the overall bends was similar, taking into account that the initial set up and final mandrel removal are the same for both materials. Overall it was concluded that the Gr. 690 could be successfully field bent without any problems.

A key requirement for the construction and installation of Gr. 690 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 was used for all mainline welds as follows:

- Internal root beads were completed using short circuit metal transfer with 75% Ar - 25% CO_2 shielding gas mixture and 0.9 mm Thyssen K-Nova wire.
- External fill passes were completed using pulsed gas metal arc welding with an 85% Ar -15% CO_2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire.
- External cap passes were completed using short circuit metal arc welding with a 75% Ar - 25% CO_2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire.
- 100^oC minimum preheat was 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 were completed with E5510-G (E8010-G), minimum preheat 100^o C maintained throughout.
- Hot passes were completed with 3.2 mm Bohler BVD 100 (E10018G).
- Fill and cap passes were completed with 4.0 mm Bohler BVD 110 (E11018G).
- The contractor ensured that there was no pipe movement until after completion of the hot pass and there was 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. Overall views of the internal and external welding are given in Figures 4 and 5. The mechanized ultrasonic inspection worked extremely well for the assessment of the Gr. 690 welds.

Figure 4. Westpath, internal welding of the Gr. 690 using the 4 head, short circuit GMAW.

Figure 5. Westpath, external welding of Gr. 690 using the single arc pulsed GMAW procedures.

One of the main applications for these high strength steels is on emerging frontiers, 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, and included a 3.6 km loop of NPS 36 Gr. 690 known as the Godin Lake loop. The NPS 36 13.2 mm Gr. 690 was ordered to the same specification as per the Westpath project with some modifications and the pipe was again supplied by JFE. Additional testing requirements were included to commence the expansion to strain based designs. The pipe was ordered to a deliberate policy of slightly lower yield strength in the longitudinal direction to maximize the strain based design approach. This project was also the start of the understanding of aging effects on high strength steels which ultimately led to the change in chemistry and processing to minimize the effect. Additional work on the tensile and compressive strain behaviour of the material was also the subject of a separate R&D program and the results are presented in a paper by Sadasue et al [20]. 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.

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 [18, 21]. 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 first field implementation of single tandem PGMAW took place on this 2 km of Gr. 690, Figure 6.

Figure 6. Application of single tandem on welding Gr. 690 Godin Lake.

The welding procedure was a combination of single-torch PGMAW for hot and first fill weld passes (using, also for the first time in the field, a CRC-Evans' partially automated P260 welding tractor) and tandem PGMAW for the second and third fill and cap pass. 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 an 85% Ar - 15% CO_2 shielding gas mixture and 1.0 mm Oerlikon Carbofil NiMo-1 wire.
- External 2^{nd} and 3^{rd} 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 ^{o}C minimum preheat shall be maintained throughout.

Tie-in procedures were as per Westpath utilizing low-hydrogen, vertical-down shielded metal arc welding for tie-ins and repair. Note subsequent to this project a mechanized flux cored tie-in procedure has been developed and validated and was implemented on the next project.

The project was welded in extreme winter conditions with temperatures as low as -45 ^{o}C and no issues with the bending or constructability of Gr. 690 were experienced, Figure 7.

Figure 7. Winter construction of Godin Lake Gr. 690 project.

All welds were inspected using 100% mechanized ultrasonics and accepted using an ECA as per Annex K of CSA Z662-03. The welding of the Gr. 690 using the hybrid procedure went extremely well and very low repair rates were achieved. There were no repairs in single-torch PGMAW passes and a total of seven repairs for lack-of-sidewall fusion in tandem PGMAW passes for a final repair rate of five percent. Although not a requirement of the project, the qualified welding procedure met the provisional targets for a high-strain design of 810MPa yield in an all-weld-metal tensile test and 0.1-mm CTOD at -10 ^{o}C. Positive feedback was received from the welding crews and no issues arose from using the high productivity processes. The next stage will be 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 Gr. 690 and Gr. 830 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 which had a similar chemistry to pipe but higher microalloy content and were quenched and tempered. 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 future projects. Normal installation of the pipeline took place in March 2004 and no difficulties were experienced with the laying of the Gr. 690.

Following on from Westpath and Godin Lake work continued with various major pipe manufacturers on key aspects of pipe production: effect of thermal aging, tensile and strain capacities, fracture behaviour, welding and construction. This effort resulted in a series of additional Gr. 690 projects being implemented, all with the aim of increasing the confidence in the production and construction of Gr. 690.

As part of the Stittsville Gr. 555 project, 5 km of Gr. 690 NPS 42 14.3 mm pipe (supplied by JFE) was installed in the summer of 2006. Based on the previous research a full strain-based specification was developed for the material and full compliance to that requirement was obtained. A similar approach to the Godin project was utilized for the pipe material, however additional requirements such as curve shape in the longitudinal direction were applied and previous information on the effect of aging was also implemented. The approach was similar to previous projects and the properties were summarized in reference [1]. The project also incorporated a "trial" of IPSCO's proposed development of spiral Gr. 690 but this was limited to 12.7 mm wall, however considerable additional development would be required on that specific material. In addition further welding trials had been performed prior to this project and the following welding approach was utilized. This was the first time tandem PGMAW was used as the mainline welding process for a complete project (including the remaining Gr. 550). The project was also the first time the fully automated, CRC-Evans' P-450 welding tractor was used. The contractor set up only a small five-shack mainline welding spread as there was a large number of crossings and changes of wall thickness, and also equipment moves to be able to complete some sections in the reverse direction to accommodate the narrow ROW and the existing pipeline. The average production over the 18 days of welding was 43 welds per day and there was no appreciable difference between the Gr. 690 and the Gr. 555. The weld repair rate for the NPS 42, 14.3 mm Gr. 690 was 6.5% and for the NPS 42, 12.7 mm Gr. 690 it was 1.2%. A combination of manual GMAW and mechanized flux-cored arc welding was used for tie-in welding and demonstrated a 50% improvement in tie-in completion times when compared to SMAW on both Gr. 555 and Gr. 690. Low-hydrogen, vertical-down shielded metal arc welding was used for repair.

As part of the North Central Corridor North Star Project winter 2009, 5 km of Gr. 690 NPS 42 14.1 mm (supplied by NSC) was installed (in combination with 71 km of NPS 42 Gr. 550). The aim of this project was to continue the expansion of the production and development of Gr. 690 with other major pipe mills and continue the work on strain based designs and winter construction. The project was welded with dual-torch PGMAW, Figure 8, on the North Central Corridor, North Star East and North Star West. This was the first project where Gr. 690 was welded with a welding spread configured for high production in terms of welds per day and the first project where the weld metal strength overmatch for a high-strain design was targeted for mainline welds.

Figure 8. Application of dual torch pulsed GMAW on North Central Corridor.

All spreads consisted of a CRC-Evans' internal welder for the root bead, P260 single-torch GMAW system for the hot pass, CRC-Evans' P600 dual-torch PGMAW system for first and second fill, P260 single-torch PGMAW system for the third fill and P600 dual-torch PGMAW system for cap passes. The same welding procedure was used for both Gr. 555 and Gr. 690 and the welding procedure qualifications met the overmatching weld metal strength and CTOD toughness requirements for a high-strain design. The mainline welding spread averaged 97 welds/day and the poor boy averaged 34 welds/day. There was no difference in welds per day between the Gr. 690 and the Gr. 555. The repair rate for Gr. 690 was 4.4%. Low-hydrogen, vertical-down shielded metal arc welding was used for tie-ins and repair.

As part of the North Central Corridor Red Earth Project in the winter of 2010, 2.5 km of Gr. 690 NPS 42 14.3 mm wall (supplied by Europipe) was installed using the same procedure as for the previous winter. The aim of this project was to continue the expansion of the production and development of Gr. 690 with other major pipe mills and continue the work on strain–based designs and winter construction. Recent projects on Gr. 555 and Gr. 690 are now successfully utilizing dual torch procedures for the mainline. No problems were experienced during any of those projects.

Summary

Extensive work has been performed on Gr. 555 and Gr. 690 which has permitted the introduction of the pipe material on several projects since the mid 1990s. Gr. 555 is now extensively utilized throughout the world. The pipe manufacturing route has followed a thermomechanically treated microalloy path based on a C-Mn-Nb approach that has achieved good mechanical properties and toughness. A similar approach has been followed by Gr. 690 although using a slightly richer chemistry and different thermomechanical treatment. The developments have now been applied to both stress-based and strain-based designs and projects, and have skillfully combined the Code required transverse properties with those required for strain-based designs in the longitudinal direction. Since 2002, in combination with the field projects, extensive work has been performed by both pipe manufacturers and TransCanada and other major pipeline companies on the technology development of Gr. 690, including all of the work on strain capacity (both tensile and compressive), strain demand, fracture behaviour, including full scale fracture tests as well as controlled integrity test loops [22, 23]. These programs have been combined with the field projects to enable the full implementation of Gr. 690 and to demonstrate that it is capable of meeting all the requirements of future projects.

Associated with these programs has been the full scale development of the field construction of Gr. 555 and Gr. 690, ranging from the introduction of single wire PGMAW, to tandem to dual tandem. These programs have demonstrated that the technology required to weld Gr. 690 pipe has reached a stage where, once on the right-of-way, there is no perceptible difference to that which would now be selected to weld lower grades of pipe. The welding processes are essentially the same, only the chemistry of the welding consumables may differ. In terms of a strain-based design for Arctic construction, the initial challenge to achieve targets of weld yield and tensile strengths for overmatching have been achieved as well as meeting 0.1-mm CTOD at -10 ^{o}C. Tie-in and repair procedures have been developed however work is required to achieve high productivity double jointing procedures.

The work has shown that Gr. 690 can be considered an option for the high pressure pipeline projects. The advantages include the overall lower material costs from not only reduced tonnage but also reduced handling costs, improved field logistics and reduced welding costs. The pipe cost may be slightly higher than Gr. 555; however the overall costs will be considerably lower. The perceived disadvantage may be the limited application of the material. However all of the major pipe mills have the capability of producing the required Gr. 690 material and all of the pipe codes now include it.

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