DESIGN, DEVELOPMENT AND CONFIRMATION OF A HIGH TOUGHNESS GAS LINE PIPE FOR ALLIANCE PIPELINE AT CAMROSE PIPE COMPANY

Alex J. Afaganis
Camrose Pipe Company
5302 – 39th Street
Camrose, Alberta, Canada, T4V 2N8

Dr. Lorne Carlson
Alliance Pipeline Limited
#400, 605 – 5th Avenue SW
Calgary, Alberta, Canada, T2P 3H5

James R. Mitchell
Camrose Pipe Company
#1060, 700 – 4th Avenue SW,
Calgary, Alberta, Canada, T2P 3J4

Alan Gilroy-Scott
Integrity Management
(Materials and Quality Management Manager and Technical Consultant to Alliance Pipeline Limited)
#1422, 510 – 5th Avenue SW
Calgary, Alberta, Canada, T2P 3S2

ABSTRACT

Through 1999, Camrose Pipe Company manufactured ~152 km (~45 000 tonnes) of 1067 x 11.4mm pipe for Alliance Pipeline Partnership Ltd. This section of Alliance's pipeline was manufactured to a design whose pipe fracture toughness requirements was significantly beyond those historically manufactured in Canada and initiated a major leap in plate/pipe manufacturing toughness capability. The development of line pipe toughness in Canada culminating in this order will be profiled.

Further, this high toughness design is at the far reaches of the traditional fracture arrest models. Besides the traditional Charpy energy measure, and to confirm Alliance's confidence in their fracture arrest design, another two sets of fracture assessment tests were used on a trial and production basis: the API chevron notch drop weight tear test (CN DWTT) energy and the energy of a similar test using an Alliance notch modification. The results of these tests will be reviewed and compared.

HISTORY OF LINE PIPE TOUGHNESS DEVELOPMENT IN CANADA

Beginning in the mid-1960s, fracture toughness criteria became recognized as important and were instituted into pipeline specifications. Initially, the emphasis was on the avoidance of brittle fractures. At the time it was generally accepted that suitable fracture control could be obtained by having pipe which exhibited fully ductile behavior when subjected to the drop weight tear test (DWTT) or the Charpy V-notch at temperatures equal to or less than the pipeline’s design temperature. Later, a shear requirement was instituted into many Canadian line pipe specifications and became the sole toughness requirement until the late 1960s. During this period of time, steelmaking and rolling practices changes were
made to increase the DWTT ductility for gas pipeline projects. These changes included moving from semi-killed steel to killed steel to improve internal cleanliness and the adoption of special low temperature “controlled rolling” techniques to produce a finer grain structure. In late 1968 and early 1970, a total of three fully ductile shear fractures occurred in gas service, with each rupture unexpectedly propagating for several hundred feet along the pipeline. After several studies it became apparent that, in addition to ductile fracture appearance, sufficient absorbed energy is required to ensure adequate fracture arrest properties. While the aforementioned switch to killed steel produced the intended effect of promoting ductile shear through reduced grain size, it promoted the presence of Type II manganese sulphide inclusions, which reduced the absorbed energy below the point where the steel could stop a running fracture.

Through considerable fundamental research, it was recognized that the primary influence on energy absorption was the quantity and shape of the sulphide inclusions in the steel. Accordingly, starting in the late 1960s, a variety of techniques were developed and used to produce pipe steels to meet the increasingly demanding requirements of the Canadian pipeline industry through the 1970s. These included various methods of sulphur removal at the hot metal stage and/or inclusion shape control (such as rare earth metal additions or calcium injections).

In the 1980s, with the advent and increased use of both strand cast slabs and basic oxygen furnace steel, further improvements in both grain size reduction/homogeneity and inclusion shape control were realized which further improved absorbed energy. Through the 1980s and into the 1990s, steelmaking and strand casting techniques have continued to be refined, particularly with regards to the further inclusion removal by flotation and tundish design and the control of reoxidation by inert gas shrouding and/or vacuum degassing. Over the same time period, a significant reduction in the steel’s carbon content further improved the pipe’s toughness. The trend in specified properties, and similarly steelmaking capability, from the 1960s through the 1990s is shown in Figure 1.

In addition, while improving the steel’s absorbed energy, the steel’s brittle-to-ductile transition temperature simultaneously improved due to the refinement and homogenization of the grain microstructure. This was a result of various microalloying and controlled rolling developments from the late 1960s through to today.[2]

ALLIANCE PIPELINE DESIGN DEVELOPMENT

Through the 1980s and 1990s pipeline designs have been primarily based on lean gas with relatively low operating pressures. These designs fell within the acceptable design criteria of the AGA and/or the AISI models[3] for fracture arrest. The Alliance pipeline was designed to transport rich, dense phase gas having a gross heating value (GHV) up to 42.5 MJ/m³ (1138 Btu/scf) at a significantly higher maximum operating pressure of 12 000 kPa (1740 psig). The pipeline material design differs for this type of transportation in that not only is the pressure higher but the decompression curve of the gas, in the case of failure, possesses a larger driving force due to the large fraction of heavy hydrocarbons in the gas. This, in turn, requires pipe with a higher toughness to arrest a running fracture.

The original 1997 design for the Alliance pipeline required a Charpy energy value (for the 1067mm diameter portion) of 176J per heat of material supplied. Further to the NEB hearings on the project, the Charpy energy was increased to 215J minimum all-heat-average (AHA) for the project. Nonetheless, Campipe agreed to provide this, based on historical experience and the recent positive trends in the industry and through trials towards higher impact values.

In addition to this higher Charpy toughness, the NEB hearings further challenged Alliance’s design criteria and prompted Alliance to conduct a full-scale burst test program in 1998. These tests directly determined the fracture propagation arrest level for the 1067mm diameter mainline portion. From associated experimental work and as a consequence of the burst test, Alliance also proposed a new full-thickness fracture arrest measure – the per unit area energy of a modified chevron notch DWTT, Figure 2. This new notch design was much sharper than the known, but little used, API chevron notch test coupon.[1] The full-scale test added a 453 J/cm² full-thickness arrest toughness to the 215J Charpy energy for the worst-case design condition. Therefore, as part of their conditions from the NEB, Alliance needed to have the pipe from Campipe meet or exceed both the 215J Charpy energy and the 453J/cm² energy value of this new modified DWTT on a production AHA basis.

LINE PIPE DESIGN DEVELOPMENT

Alliance’s dual arrest toughness requirements posed two fundamental problems: development of line pipe to meet a high toughness value beyond industry state-of-the-art, and further to commit to meet an unknown toughness measure at a presumed equivalent high toughness level. Addressing the first point of a higher Charpy toughness, the approach and development path was more traditional in terms of extending known technological capabilities. The Charpy measure possessed known, though not fully confirmed, relationships to chemistry and thermomechanical manufacturing practices. The key points in this development was the use of tightly controlled composition (especially impurities such as phosphorus and sulphur) and rolling practices. Addressing the second point of committing to meet an unknown toughness measure required the acceptance of considerable risk and a more dynamic development approach. At the time of commitment to this toughness measure, only very limited correlations to this new toughness measure had been developed. Campipe (along with Alliance and our suppliers)
chose to aim to an even higher Charpy toughness (215J aim minimum as opposed to AHA) to mitigate the potential risk associated with a downside error in the relationship between the new Alliance CN DWTT energy/area and Charpy energy. The practical considerations in this regard were defining and conforming to extremely tight controls on both composition and manufacturing practices. An example of this was the rejection of approximately 10% of one supplier’s plate due to minor but potentially significant composition non-compliance.

FULL-SCALE PIPE TRIALS

In late 1998, Campipe initiated discussions with several plate manufacturers to determine their capability and potential to produce skelp for Alliance’s high toughness pipe application of 200F AHA Charpy energy. These discussions later included Alliance and were conducted with both domestic and foreign suppliers - in some cases with independent slab suppliers. The initial meetings were arranged to discuss the technical requirements, steelmaking/plate mill capability, as well as assess quality and logistics systems.

After the initial meetings with potential plate/slab suppliers, the suppliers designed steels to meet the then (1998) Alliance pipeline design requirements and many conducted in-house plate rolling trials to assess capability. The results of these plate trials were then evaluated with plate-to-pipe mechanical property predictor models, the experience of plate and pipe mill metallurgists, and/or preliminary full-scale pipe trials on the Campipe mill.

Later, well into Campipe/supplier trials, the NEB hearing conditions directed Alliance to not only comply with a higher Charpy energy but additionally meet a full thickness energy requirement (CN DWTT) the criteria for which evolved from Alliance’s research program and associated full scale burst tests. (See Alliance Pipeline design section above.) Although Campipe had some reservations about the revised criteria, they evaluated the technical capability of the suppliers from initial trials and the potential risk of not meeting these criteria, and accepted these new unproven criteria. The technical and commercial risk was significant as the toughness relationships were in their infancy and capability was essentially uncertain. The critical design consideration now became the development of the toughness relationship between the chemistry/processing parameters and the modified CN DWTT energy and the attainment of the specified levels.

Full-scale pipe trials continued through the first quarter of 1999 to evaluate material from a series of 5 integrated slab-plate mills and 3 additional slab manufacturing facilities from Canada, the USA, Japan, and Europe. Several trial stages were taken to refine practices to achieve desired properties. As the trials progressed, an improved understanding of the critical chemistry/processing parameters evolved. Ultimately, the required properties were achieved. At each stage, there was open communication between Campipe, Alliance and potential suppliers, as these were often new supply relationships, and as the design requirements evolved and further challenged the skelp manufacturers’ capabilities.

The transverse pipe body mechanical properties of these trials are presented in Table I along with final aim pipe design requirements. Based on the results and commercial/logistical considerations, suppliers C, E, and F were chosen for the order with a roughly 40-50-10% split between the suppliers.

It should also be noted that there were no significant modifications to the pipe manufacturing/welding processes to produce this product.

PIPE PRODUCTION

Production of the 1067 x 11.4mm pipe was completed between July and November 1999 without significant production issues. The strengths of the pipe from the three chosen suppliers were similar (within 13 MPa on average) and both the Charpy and CN DWTT toughness were well above minimum requirements, Table II. All totalled, over 90% of the pipe for the order are predicted to arrest a running fracture based on both the Charpy and Alliance CN DWTT energy specifications. This is much higher than the designed >50% fraction.

The mean pipe toughness transition data for each supplier (Table III) confirms that the specification temperature is well above the minimum temperature of full ductility.

It is interesting to note that even at the -5°C (M5C) specification temperature, there is some amount of rising shelf with all fracture arrest toughness measures. This can be seen by comparing the average Charpy, API and Alliance CN DWTT energies (per unit area) at -5°C from Table II to energies at 85% ductile (85% SATT) and fully ductile (CVI, API, and Alliance CN DWTT) from Table IV. The weighted average Charpy, and API & Alliance CN DWTT energy increase from that at the minimum fully shear temperature is 563, 92J/cm², and 1453J/cm², respectively.

One other interesting note from Table III is that the API CN DWTT transition temperatures appear to be significantly lower than the Alliance CN DWTT temperatures. This is likely influenced by the different load capacities of the two DWTT machines used. All API CN DWTT specimens were broken on the ~737J/cm² load limit Campipe machine, whereas the Alliance CN DWTT specimens were broken on the ~1800J/cm² load limit Welland Pipe Limited machine. The lower Campipe machine capacity appears to significantly reduce the fracture speed (strain rate) of such high API CN DWTT toughness sample. This increases the fracture face ductility and thereby lowers the transition temperature. This effect has been investigated in recent papers.[3,4]

TOUGHNESS CORRELATIONS

Due to the quantity of overlap testing conducted for the order, an opportunity was available to compare the toughness responses of three fracture toughness measures: full-sized
Charpy, and API & Alliance-modified chevron notched drop weight tear tests.

a) Charpy versus API Chevron Notch DWTT Energy

The combination of the API CN DWTT coupon and the Campipe machine was chosen for production assessment of sample ductility for CSA category II toughness requirements as the machine was not consistently capable of breaking the PN DWTT samples. The pipe transverse body API CN DWTT energy measure compared to the similar Charpy energy measure at the -5°C (M5C) specification temperature is shown in Figure III (all test results fully ductile).

Observe that the correlation is not linear at higher energy values. This is evident when compared to the similar (overlaid) API 5L3 correlation.[5] The proposed primary cause of this is the proximity of the CN DWTT and Charpy energy values to their respective machine load limits.

b) Charpy versus Alliance CN DWTT Energy

A comparison was made between the Charpy energy and the Alliance CN DWTT energy per unit area, Figure 4. All Alliance CN DWTT specimens were tested on Welland Pipe Limited machine. The Welland Pipe machine load limit is well above the pipe toughness such that the correlation between the two variables was more linear, equation 1.

\[ E/A_{Alliance} (J/cm^2) = 2.77 E_A (J) - 0.00319 E_A^2 (J^2) \]

\[ R^2 = 0.49; \text{ standard error of estimate} = 44 \text{ J/cm}^2 \]

A possible cause of the non-linear relationship is similar to that discussed earlier for DWTT machines breaking samples with toughness near the machine load capacity. (The load capacity of Campipe’s new Charpy impact machine is 540J.) Nonetheless, at the Charpy arrest value of 215J, this correlation (equation 1) predicts an Alliance CN DWTT energy value of 448J/cm² ± 44J/cm² standard error. This result is consistent with the measured value of 453J/cm² from the arrest pipe of the Alliance full-scale burst test.

c) API versus Alliance CN DWTT Energy

A comparison was made between the API CN DWTT and the Alliance CN DWTT energies per unit area, Figure 5. There is a consistent correlation; the Alliance notch energy/area being approximately 90% of the API notch energy, equation 2.

\[ E/A_{Alliance} (J/cm^2) = 0.90 E/A_{API} (J/cm^2) \]

\[ R^2 = 0.36; \text{ standard error of estimate} = 41 \text{ J/cm}^2 \]

CONCLUSIONS

1. Successful pipe manufacture for modern technology pipeline designs (such as the Alliance Pipeline) demand an ongoing dialogue between suppliers and customer, full-scale trials, and the assessment, mitigation and ultimate acceptance of considerable risk.

2. Clear correlations were made between Charpy energy and Alliance CN DWTT energy per unit area, and between API and Alliance chevron notch DWTT energy per unit area. The results validate the Alliance fracture design and also provide a platform for the definition of future pipe fracture designs.

ACKNOWLEDGEMENTS

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REFERENCES


Table I: Average Trial Transverse Pipe Body Mechanical Properties

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>M5C f/s Charpy Energy (J)</th>
<th>85% Charpy SATT (°C)</th>
<th>API CN DWTT 85% SATT (°C)</th>
<th>M5C Alliance CN DWTT Energy/Area (J/cm²)</th>
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<tbody>
<tr>
<td>A</td>
<td>566</td>
<td>681</td>
<td><strong>184</strong></td>
<td>-75</td>
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<tr>
<td>B</td>
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Aim average  515-545 >613 >225 <-50 <-20 >500

Specified
* production results
** PN DWTT results

note: All PN and API CN DWT tests conducted on Campipe's DWT machine while Alliance CN DWT tests conducted on Welland Pipe Limited's DWT machine

bold italicized text identifies pipe results beyond aim average values

Table II: Average Production Transverse Pipe Body Mechanical Properties

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Yield Strength (MPa)</th>
<th>Tensile Strength (MPa)</th>
<th>M5C f/s Charpy Energy (J)</th>
<th>M5C API CN DWTT Energy/Area (J/cm²)</th>
<th>M5C Alliance CN DWTT Energy/Area (J/cm²)</th>
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<tr>
<td>C</td>
<td>531</td>
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<td>296</td>
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<tr>
<td>E</td>
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<td>618</td>
<td>340</td>
<td>600</td>
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<tr>
<td>F</td>
<td>536</td>
<td>630</td>
<td>281</td>
<td>573</td>
<td>521</td>
</tr>
</tbody>
</table>

Weighted Average  538 624 317 591 542

Specified min ≥483 ≥565 ≥215 (AHA) none ≥453 (AHA)

% Arrest  n/a n/a (94%) 100% (91%)
Table III: Average Production Transverse Pipe Body Toughness Transition Results

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Full-sized Charpy Energy (J)/Temp (°C)</th>
<th>API CN DWTT Energy/Area (J/cm²) / Temp (°C)</th>
<th>Alliance CN DWTT Energy/Area (J/cm²) / Temp (°C)</th>
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</thead>
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<tr>
<td></td>
<td>85% SATT CVI 85% SATT API CN DWTT</td>
<td>85% SATT API CN DWTT</td>
<td>85% SATT Alliance CN DWTT</td>
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<tr>
<td>C</td>
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<td>F</td>
<td>183/-75 231/-60 381/-75 409/-60</td>
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</table>

Weighed average 180/-66 261/-42 378/-63 499/-42 303/-33 <397/-28

CVI, API DWTT, Alliance DWTT are defined as the Charpy/API CN DWTT/Alliance CN DWTT Energy (Energy/Area) at minimum temperature of full ductility.

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Figure 1: Generalized Canadian Pipeline Specification Trend (1965 - 1999)
Figure 2: Alliance-modified Chevron Notch DWTT Coupon Details

Figure 3: Correlation between Charpy Energy and API Chevron Notch DWTT Energy/Area

- 737J/cm² - estimated CPC machine load limit
- 590J/cm² - estimated 80% of CPC machine load limit
- API correlation in 5L3 for 0.450°

43J = 80% of Machine Load Limit
Figure 4: Correlation between Charpy Energy and the Alliance-modified Chevron Notch DWTT Energy/Area

\[ \text{Alliance CN E/A (J/cm}^2\text{)} = 2.77 \text{ Ev (J)} - 0.00319 \text{ Ev}^2 (\text{J}^2) \]
\[ R^2 = 0.49; \text{ stderr of } y = 44 \text{ J/cm}^2 \]

1000 J/cm² - estimated 55% of WPL machine load limit

590 J/cm² - estimated 80% of CPC machine load limit

Figure 5: Correlation between Alliance-modified and API Chevron Notch DWTT Energy/Area

\[ \text{Alliance E/A (J/cm}^2\text{)} = 0.90 \times \text{ API E/A (J/cm}^2\text{)} \]
\[ R^2 = 0.36; \text{ stderr of } y = 41 \text{ J/cm}^2 \]

1000 J/cm² - estimated 55% of WPL machine load limit

737 J/cm² - estimated CPC machine load limit

900 J/cm² - estimated 80% of CPC machine load limit