



TECHNOLOGY *for* FUTURE *and* AGEING PIPELINES

19-21 October 2021 Gent | Belgium

MANAGING STANDARDS WITH EVOLVING INDUSTRY PRACTICE – LESSONS LEARNED FROM GIRTH WELD FAILURES IN NEWLY CONSTRUCTED PIPELINES

Yong-Yi Wang¹ and Dan Jia¹

¹ Center for Reliable Energy Systems, Dublin, Ohio, USA

ywang@cres-americas.com

ABSTRACT

There have been at least 10 girth weld incidents in newly constructed pipelines in North America. Similar incidents have occurred in Asian and South America. In total, at least 30 such girth weld incidents are known to have occurred in newly constructed pipelines, including in-service failures and hydrostatic test leaks. The primary contributors to the failures in North America are (1) weld strength undermatching, (2) heat-affected zone (HAZ) softening, and (3) elevated stress/strain in the affected girth welds.

The girth weld failures have exposed gaps or disconnects among standards that govern the different phases of a pipeline's life. For instance, the selection of pipes for welding procedure qualification in most of the current standards makes no connection with the possible strength range of the linepipes, while the linepipe standards permit a large range of strength for a given grade of linepipes. Another example is that the welding procedure qualification requirements can be inadequate for loads imposed on the welds under realistic field conditions. The requirements in the customary stress-based design do not reflect these field conditions either. Some of these gaps are exacerbated by the continuously evolving industry practice, such as linepipe manufacturing and field girth welding. For instance, girth welding standards have historically focused on the detection and prevention of weld flaws. However, many of the girth weld failures mentioned above did not involve flaws of discernible size.

This paper is intended to promote fresh thinking in reference to some well-established assumptions which may not be well-founded as demonstrated by newly available data. The paper starts with a brief review of girth weld incidents and contributing factors. Elements in current standards that are relevant to those contributing factors are examined. The paper closes with a brief summary of identified gaps and proposes possible changes to relevant standards.

KEYWORDS

Pipeline, standards, new and ageing pipelines, girth weld failures

1. INTRODUCTION

There has been an increase in girth weld incidents in newly constructed pipelines, including in-service failures and hydrostatic test leaks. These failures have exposed gaps or disconnects among standards that govern the different phases of a pipeline's life. For instance, the selection of pipes for welding procedure qualification in most of the current standards makes no connection with the possible strength range of the linepipes, while the linepipe standards permit a large range of strength for a given grade of linepipes. Another example is that the welding procedure qualification requirements can be inadequate for loads imposed on the welds under realistic field conditions. The requirements in the customary stress-based design do not reflect these field conditions either. Some of these gaps are exacerbated by the continuously evolving industry practice, such as linepipe manufacturing and field girth welding. For instance, girth welding standards have historically focused on the detection and prevention of weld flaws. However, many of the girth weld failures mentioned above did not involve flaws of discernible size.

The gaps in the current industry practice and standards are analyzed and possible updates to these standards are proposed in this paper.

2. GIRTH WELD FAILURES IN NEWLY CONSTRUCTED PIPELINES

2.1. Girth Weld Incidents

There have been at least 10 girth weld incidents in newly constructed pipelines in North America [1]. Girth weld incidents in newly constructed pipelines have also occurred in Asia [2,3] and South America [4]. In total, at least 30 girth weld incidents are known to have occurred in newly constructed pipelines, including in-service ruptures and hydrostatic test leaks.

2.2. Contributors to the Girth Weld Incidents

Details for some of the incidents in North America have been reported and analyzed in prior publications [5,6,7,8]. Among the 10 girth weld incidents that occurred in North America, there were 6 in-service ruptures, 1 in-service leak, and 3 hydrostatic test leaks [9]. All of the failed girth welds were fabricated with manual welding processes. Nine welds were fabricated with SMAW processes using E6010 for the root pass and E8010 for the remaining passes, and the remaining X70/X80 weld was fabricated with an SMAW E6010 root and FCAW-G for the remaining passes.

Girth weld failures occur when the strain demand on the girth welds exceeds the strain capacity of the welds. Both strain demand and strain capacity refer to nominal strains measured in a segment of a pipeline away from the weld region, i.e., global strain. The strain demand is generated from the extension and bending of the pipeline segment caused by pipeline operational and support conditions, such as settlements. The tolerance to the strain is primarily controlled/determined by whether the extension and bending of the pipeline segment is accommodated by the entire pipeline segment or by a small region around the girth welds. When there is weld strength undermatching, HAZ softening, and/or large weld flaws, the deformation of a pipeline segment can cause high strain concentration in the girth weld region and ultimately lead to failure if the strain is sufficiently high. Much greater deformation can be accommodated if such deformation is shared along the entire pipe segment when the girth welds do not become the location of high strain concentration.

Table 1 summarizes a few major factors affecting the strain capacity and strain demand and their relative contribution to the girth weld incidents [10]. For instance, "weld strength undermatching" is a primary contributor to 6 out of the 10 incidents in North America, a secondary contributor to 1 incident, and not a factor in 2 incidents. The level of weld strength undermatching is not known for 1 incident at this time. Other contributing factors are characterized in a similar format. The major contributors to these incidents are (1) weld strength undermatching, (2) heat-affected zone (HAZ) softening, and (3) elevated external load.

Table 1 Summary of contributing factors to the 10 North American girth weld incidents

Contributors		Primary	Secondary	Not a Factor, Not Applicable	Not Sure
Tensile Strain Capacity	Weld Strength Undermatching	6	1	2	1
	HAZ Softening	7	1	1	1
	Girth Weld Flaw	1	0	9	0
Strain Demand	External Load	3	4	1	2

3. LONGITUDINAL STRAIN/STRESS – ACTUAL FIELD CONDITIONS VS. DESIGN

3.1. Longitudinal Strain/Stress – Field Conditions

In-line inspection (ILI) inertial measurement unit (IMU) surveys indicate that there can be many locations in a pipeline with longitudinal strains exceeding the typical design limit of stress-based design pipelines. Even in flat Texas farmland, strain features exceeding the design stress limit of 90% SMYS (equivalent to about 0.20% total strain) are shown to occur once in every 1-2 miles of pipeline on average [11]. A similar frequency of strain features is also observed in newly constructed pipelines [11]. Even for pipelines not subjected to geohazards, the median value of bending strain can reach 0.20%. The corresponding median value of the total strain would be around 0.25-0.30% after adding the uniform extensional strain of 0.05-0.10% not captured in the reported bending strains. The uniform (around the circumference) extensional strains are caused by internal pressure, temperature differentials between operation and construction, and other ROW (right of way) conditions. The high end of bending strain is in the range of 0.30-0.35%, giving a total strain of 0.35-0.45%. Geohazards, such as landslide or subsidence, could produce longitudinal strains greater than 1.0%.

Theriault, et al., reviewed 4618 bending strain features reported by the three largest North America IMU survey providers to assess their relationship with possible geohazard locations [12]. The reporting threshold for the bending strain was 0.125%. Because the uniform extensional strain of 0.05-0.10% is not captured in the reported bending strains, this reporting threshold can be approximately viewed as the design limit of 0.2% total strain, or 90% SMYS in stress. The overall correlation between likely geohazards and reported bending strain features is low at 298 features out of 4618 reported features (6%). Most of the strain features are thought to be related to pipeline construction, such as roping in tie-in welds, natural settlement after construction, and post-construction excavation and backfill. The correlation between likely geohazards and reported bending strain features rises sharply with increasing strain magnitude. At a bending strain value greater than 0.35%, the correlation between likely geohazards and reported strain features is over 50%. At a bending strain value greater than 0.42%, the correlation is over 90%. This work indicated that strain features exceeding the design limit are fairly common. If IMU is used as a tool to manage geohazards, the action threshold would ideally be 0.35% bending strain, or 0.425% total strain or higher in order to avoid “over-reacting” to reported strain features. This ideal action threshold is significantly greater than the design requirement of 0.20% strain.

3.2. Design for Longitudinal Strain/Stress – Code and Design Requirements

US Federal Codes, i.e., CFR Part 192 and CFR Part 195, and ASME B31.4 and B31.8 require special design and construction against abnormal loads imposed on pipelines from natural hazards, such as washouts, floods, unstable soil, landslides, and seismic activities. [13] For pipeline segments traversing regions with a large number of ground movements, such as the Appalachian Mountains in the eastern US, special design or construction practices are

frequently not performed, either due to difficulties in completely identifying those sites or practical issues due to the sheer number of sites. Instead, the design usually falls back to traditional stress-based design. For traditional stress-based design pipelines, the longitudinal stresses and combined stresses are limited to 90% SMYS or less in ASME B31.4 and B31.8. ASME B31.4 and B31.8 also permit pipelines to be designed for strains up to 2.0%, provided conditions stated in the standards are met. The standards, however, do not state how these conditions can be met. This ambiguity and lack of specific requirements could be another reason for not exercising special designs beyond the customary 90% SMYS stress limit.

4. LINEPIPE STANDARDS – STRENGTH, CHEMICAL COMPOSITION, AND STEEL PROCESSING

4.1. Strength of Linepipe

The permitted yield strength and ultimate tensile strength (UTS) ranges for a given grade of PSL2 pipes is shown in Figure 1. For grades of X52 and above, the yield strength has a range of 22 ksi or greater. The permitted range of UTS is nearly 30 ksi or greater. In most cases, the yield strength is obtained from flattened hoop specimens. The actual yield strength of pipes could be 4-10 ksi higher than the reported values from these flattened specimens [14]. Therefore, it is possible, although may not be common, that the actual yield strength and UTS are nearly 30 ksi above the specified minimum values.

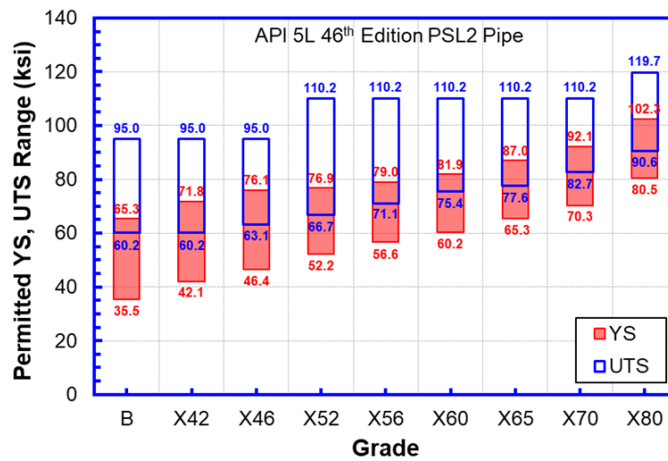


Figure 1 Permitted ranges of yield strength and UTS for PSL2 pipes in API 5L

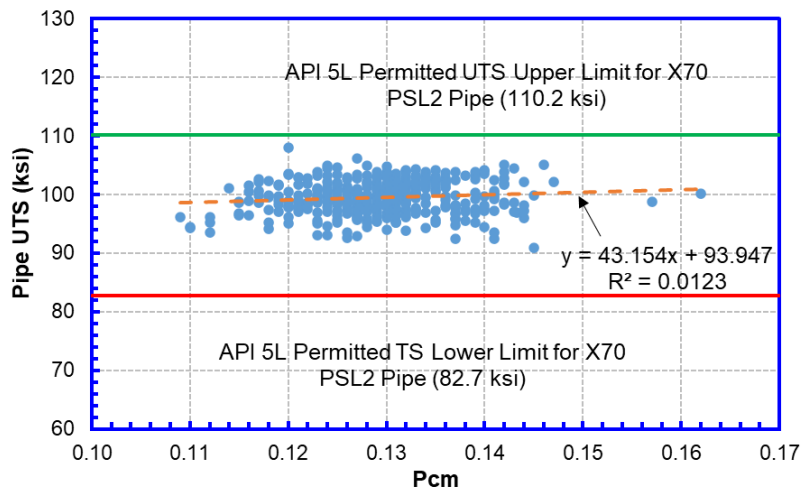


Figure 2 UTS of 24-inch OD ERW X70 PSL2 pipes as a function of Pcm

The actual UTS for 24-inch OD ERW X70 PSL2 pipes installed on a project in 2010's as a function of corresponding Pcm is shown in Figure 2. The UTS and Pcm were from MTRs and the UTS was measured in pipe hoop direction. The pipes were supplied by one manufacturer and the data contained nearly 400 heats of steels. It is not known at the time of this writing if the coils were made by one or more steel supplier(s) and the duration over which the pipes were manufactured. These data reflect the mechanical properties and chemical compositions of the installed pipes on this particular project. They should not be interpreted as cause-and-effect relationship between UTS and chemical composition. The UTS has a range of 90-108 ksi with a median value around 100 ksi. The specified minimum UTS for X70 pipes is 82.7 ksi.

A large number of MTRs grouped by construction projects have been reviewed at CRES. In most cases, the median UTS for X70 pipes is in the range of 90-95 ksi. In a minority number of projects, the median UTS for X70 pipes is as high as 103 ksi. The standard deviation (SD) of UTS is usually in the range of 2-3 ksi. In most cases, a mean + 2SD would put the UTS at around 94-99 ksi. In a minority number of cases, a mean + 2SD could put the UTS at nearly 110 ksi, which is the upper limit UTS for X70 PSL2 pipes.

4.2. Steel Manufacturing - Chemical Compositions and Steel Processing

Linepipe steels are typically manufactured well within the chemical composition limits in linepipe standards, such as API 5L. There are many different ways to achieve the required mechanical properties through a combination of alloying strategies and rolling and cooling practices. There is not necessarily a unique relationship between chemical composition and the strength of pipes. Figure 2 shows that there is a very weak relationship between the UTS and Pcm for the pipes installed on this one project. An increase of 0.01 in Pcm corresponds to an increase of 0.43 ksi in UTS. There are much greater variations in strength for a given value of Pcm than the strength change with respect to Pcm. The correlation between the UTS and Pcm is quite poor, reflected in the very low R^2 value of the linear fit.

The observed general trend after reviewing a large number of pipe MTRs is that high-grade heavy-wall pipes tend to have relatively "richer" chemistry than lower-grade thin-wall pipes as measured by Pcm. However, for pipes installed on a particular project, there may or may not be a correlation between strength and Pcm.

5. GIRTH WELDING PROCEDURE QUALIFICATION REQUIREMENTS AND IMPLICATIONS

5.1. Requirements in API 1104

The main body of API 1104 [15] requires welding procedure qualification by either grouping multiple pipe grades if the pipe grade is lower than X65, or pipe grade if the grade is equal or greater than X65. Failure in the weld area is permitted in cross-weld tensile tests during welding procedure qualification provided the nominal failure stress is greater than the specified minimum tensile strength (SMTS) of the pipe grade being qualified.

Annex A of API 1104 has more stringent welding procedure qualification requirement, primarily for the purpose of ensuring consistently adequate fracture toughness. The requirements for cross-weld tensile tests are largely similar to those in the main body of the standard, except for the retesting options. Annex A has a footnote advising against having grossly undermatching weld metal strength, but it does not state how the undermatching should be evaluated.

Annex A of API 1104 also requires requalification of welds if the Pcm of the steel is increased by more than 0.02 for microalloyed steels. The rationale for this provision is that HAZ toughness may decrease due to the increase in Pcm. There is no consideration of the potentially negative impact of HAZ softening from steels with reduced Pcm.

5.2. Requirements in CSA Z662

There is no mandatory weld metal overmatching requirement in CSA Z662 [16]. The requirement for cross-weld tensile test specimens in the main body of CSA Z662 states:

“The tensile strength of test specimens shall be equal to or greater than (a) the SMTS of the base metal; (b) the SMTS of the weaker of the two base metals; or (c) 95% of the SMTS of the base metal if the location of failure occurs outside the weld and HAZ.”

Annex K of CSA Z662-15 has more stringent requirements for cross-weld tensile tests:

- (1) The reinforcement on both sides of the specimen (OD and ID) must be removed.
- (2) The specimen shall not fail in the weld.
- (3) The tensile strength for each test shall be equal to or greater than the specified minimum tensile strength of the pipe material. The tensile strength is not allowed to fall below 100% SMTS whereas the main body would allow a tensile strength as low as 95% SMTS if the failure is outside the weld and HAZ.

All three requirements in Annex K are a significant step-up in comparison to the requirements in the main body, particularly the requirement of not failing in the weld and the removal of the weld reinforcement. For an X70 pipe with a median UTS 10 ksi above the SMTS (at 92 ksi = 82+10 ksi), the removal of weld reinforcement and the requirement of not failing in the weld would likely add approximately 15 ksi to the weld metal strength to meet the minimum requirements of Annex K compared to the minimum requirements of the main body.

5.3. Requirements in European Standards

There are no mandatory requirements for weld metal strength overmatching in EN 12732 [17]. The standard recommends choosing overmatching welding materials and the operator can require the use of the Annex G where the EPRG weld defect assessment criteria are listed. The standard states:

“Unless otherwise agreed, matching weld metal for girth welds shall be required. The use of overmatched consumables is recommended. Weld metal overmatching can be a welding procedure qualification requirement of the pipeline operator, for example when using the EPRG girth defect acceptance criteria (Annex G).”

When an operator chooses to use Annex G in EN 12732, the requirements default to EPRG guidelines. EPRG Guidelines-1996 [18] requires that the yield strength of the weld metal at Tiers 2 and 3 should be equal to or greater than the yield strength of the pipe material, i.e., weld metal strength overmatching at yield level. However, the specifics of achieving such requirements were not given. It is well known that the yield strength of the pipe and weld metal can be affected by many factors, such as test specimen type, size, location from which the specimen is extracted, method of specimen preparation, instrumentation, and post-test data processing. [14,19]. The requirements would be difficult to implement without defining the specifics. EPRG Guidelines-2014 [20] provides more specific guidance to achieve weld yield strength overmatching, including:

- The yield strength of the weld metal should be measured using a round-bar all-weld-metal tensile specimen.
- The yield strength of the pipe should be measured in the longitudinal direction using full-thickness strip specimens.
 - The use of correlation between hoop and longitudinal yield strength is permitted with full considerations of the unique relations for different types of pipes, such as seamless, SAWL, SAWH, and ERW pipes.
- The minimum yield strength of the weld metal should be greater than the minimum pipe yield strength in the longitudinal direction plus five standard deviations.
 - The standard deviation can be assumed to be 20 MPa if a value cannot be obtained from production test data.

The 2014 recommendation would ensure weld strength overmatching if the scatter in the yield strength distributions is less than 120 MPa [20]. A potential challenge to the overmatching requirement is that, given the large scatters possible in the reported yield strength of pipe and weld metal, the weld metal strength may need to be

significantly higher than the pipe strength on average to ensure the lowest weld metal yield strength is no less than the lowest pipe yield strength plus 5 standard deviations.

5.4. Requirements in Australian Standards

AS/NZS 2885.2:2020 [21] does not have a mandatory weld metal overmatching requirement. The main body of AS/NZS 2885.2:2020 states the criteria of acceptance for cross-weld tensile specimens is:

“Where the test specimen breaks in the weld metal or the heat-affected zone, the tensile strength shall be not less than (i) where the parent metals have the same SMTS, the SMTS of the parent metal; (ii) where the parent metals have differing SMTS, the lower SMTS of the parent metals; or (iii) where the test specimen breaks outside the weld metal or heat-affected zone and where the tensile strength is less than 95% of the SMTS of the parent metal, the cause shall be investigated and reported.”

The requirement in the main body of AS/NZS 2885.2:2020 states that the cross-weld tensile test shall be carried out in accordance with:

“(i) where the diameter of the pipe is greater than 33.4 mm, the test specimen shall conform to AS 2205.2.1 (NOTE: Where the diameter of the pipe is not greater than 33.4 mm, it is recommended that a full section test specimen is used. (ii) Dressing of the face and root surfaces of the test specimen is optional expect where the criteria of acceptance for girth weld discontinuities is Tier 2 in which case the reinforcement shall be removed from both surfaces.”

There is a requirement of reporting cross-weld tensile tests in the main body of AS/NZS 2885.2:2020, which states “the report shall include the identification of the welding procedure, the welder or operator, and the location of the fracture and whether the weld is dressed.”

5.5. Implications for Tensile Strain Capacity

None of the reviewed standards have mandatory requirements for weld strength matching or overmatching against the actual strength of the pipes. With the exception of Annex G of EN 12732, no standards require all-weld-metal tensile tests either. With the current practice, the level of weld strength mismatch is at best approximated by the failure location of the cross-weld tensile tests. Some may interpret a failure outside the weld region as evidence of weld strength overmatching. Such an interpretation may seem straightforward, but it is imprecise. Failure outside the weld area is possible if the weld metal strength is slightly lower than the pipe strength due to the effect of weld cap reinforcement. Even when such interpretation is taken at its face value, a failure outside the area can only demonstrate that the weld area is no weaker than the particular piece of pipe from which the qualification weld is made. Since the actual pipe strength in a qualification test is often not reported and the pipe strength can have a wide range for a given grade, welding strength undermatching, sometimes high levels of undermatching, is still possible even when the qualification welds failed outside the weld region.

When the weld strength undermatching is 15% or greater, the expected tensile strain capacity can be as low as 0.25-0.30% [22]. Most production welds are expected to have a weld strength undermatching of less than 15%. The TSC of most welds is expected to be higher than 0.25-0.30%.

6. HAZ SOFTENING – REQUIREMENTS AND IMPLICATIONS

6.1. HAZ Hardness as a Function of Chemical Composition

The relationship between minimum hardness in HAZ and chemical composition has been examined. Figure 3 shows the measured minimum hardness in HAZ grouped by steel grade and Pcm [23]. The different bars in each group were obtained from steels subjected to different cooling rates as measured by T₈₅ (cooling time from 800 °C to 500 °C). There is an overall increase of hardness with the increase in Pcm. A similar trend is observed by Hamada, et al. as shown in Figure 4 [24]. Recent work at the University of Wollongong shows an increase in minimum hardness with

the increase in Pcm as given in Figure 5 [25]. Although the relationship between the minimum HAZ hardness and Pcm is far from unique, the general trends are fairly clear.

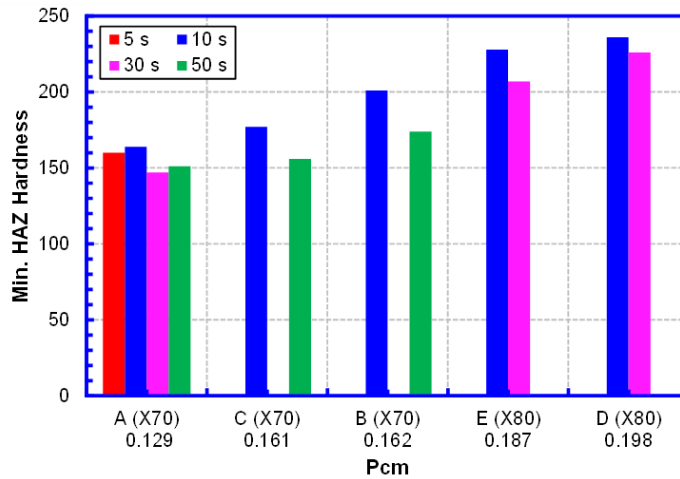


Figure 3 Minimum HAZ hardness grouped by pipe grade and Pcm using data from Reference [23]

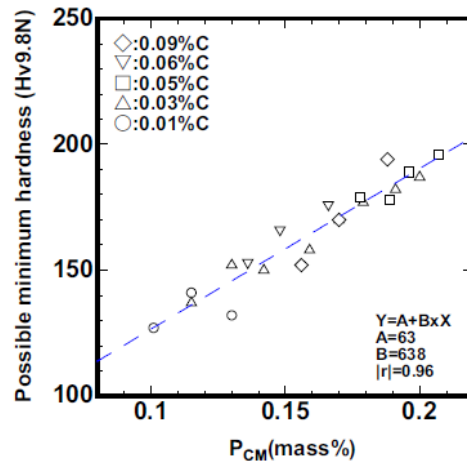


Figure 4 Possible minimum hardness as a function of Pcm for steels with different carbon content [24]

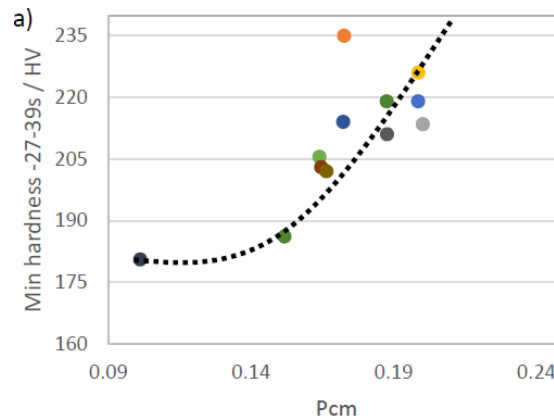


Figure 5 Minimum hardness as a function of Pcm [25]

6.2. HAZ Softening as a Function of Chemical Composition

HAZ softening occurs with microstructure changes in the HAZ when the material is subjected to welding thermal cycles. HAZ softening in girth welds has been widely reported. The level of softening is related to the chemical composition and steel manufacturing process. If a steel starts with lean chemistry and is processed to have high strength, the HAZ softening level is expected to be higher than a steel with richer chemistry that has been processed to the same strength level with the same welding thermal cycles. Similarly, steels with lean chemistries that have been processed to lower strength are expected to have lower levels of HAZ softening.

HAZ softening has not received the same level of attention as high hardness in the HAZ which can lead to increased propensity of cracking and low fracture toughness. Pipeline girth welding standards such as API 1104, CSA Z662, EN 12732, and AS 2885.2 have no limit on minimum HAZ hardness. There are no qualification tests and associated criteria to limit the level of HAZ softening in either linepipe standards, such as API 5L and CSA Z245.1, or girth welding standards.

7. POSSIBLE UPDATE IN STANDARDS

7.1. Highlights of Identified Gaps in Current Practice and Standards

A few key gaps are identified in the current practice and standards:

1. For onshore pipelines, it is not rare to see pipe segments that experience longitudinal strains greater than the design limits, i.e., a total strain of 0.2%, implied by customary stress-based design,
2. Managing strains to a level within traditional design limits can be difficult with the current ILI tools for two reasons: (1) there are too many sites with strains greater than the design limit and (2) strain features reported by ILI may not represent active threats at the low reportable strain values.
3. Linepipes are allowed to have a wide strength range for a given grade. There is no requirement to consider this range in girth welding procedure qualifications.
4. Girth welding qualification requirements would only “guarantee” a tensile strain capacity of 0.25-0.30%, although many welds in pipelines generally have higher TSCs.
5. The relative level of mechanical property requirements between manual and mechanized does not consider many real-world factors that affect the overall quality of welds. The material property requirements for both tensile and fracture toughness are usually higher for welds accepted by alternative flaw acceptance criteria such as API 1104 Annex A and CSA Z662 Annex K than welds accepted by the workmanship flaw acceptance criteria. The rationale is that the maximum permitted flaw dimensions in alternative flaw acceptance criteria are greater than the those in the workmanship criteria. This argument overlooks other factors that contribute to overall weld quality. For instance, alternative flaw acceptance criteria are often applied to fully mechanized welds which tend to have more consistent mechanical properties than manual welds which are frequently accepted by workmanship criteria. Mechanized welds are more likely to be inspected by AUT which tends to detect planar flaws better than radiography. Manual welds are more likely in locations with high stresses and restricted access, such as tie-in locations. Welds joining pipes with different wall thickness and joining pipes and fittings are also more likely to be manual welds.

7.2. Possible Updates in Design Requirements

It is evident from IMU runs that strains up to 0.35-0.40% are not rare even in the absence of geohazards in onshore buried pipelines. Reliably detecting strains below this value is a challenge. Mitigating sites with strains below the threshold of reliable detection should not be an expectation. It is suggested that the design requirement for buried

onshore pipelines should be set at 0.5% total strain¹. This requirement can be relaxed to 0.2% strain or 90%SMYS stress for welds with well-constructed supports, such as welds in stations or above-ground welds.

When a pipeline has a minimum strain capacity of 0.50%, there would be much fewer sites that would trigger remediation actions. Moreover, the remediation would likely be to address real threats to pipeline integrity.

7.3. Possible Updates in Linepipe Specifications

Reducing the upper limit of linepipe strength can reduce the likelihood of weld strength undermatching. A maximum yield strength and UTS limit of 17 ksi (117 MPa) above the specified minimums is a reasonable target. Due to possible differences between hoop and longitudinal tensile properties, these limits should be applied to tensile properties in the longitudinal direction.

Although there is no unique correlation between chemical composition and HAZ hardness, X70 steels with compositions with a P_{cm} greater than 0.140 are expected to have lower levels of HAZ softening than steels with lower P_{cm}.

Due to the complex relationships between HAZ softening and chemical composition and steel processing, a qualification test with a range of possible cooling rates representing field girth welding conditions can be useful to ensure linepipe steels have a minimum level of resistance to HAZ softening. Such a test must be designed to reflect field welding conditions and define criteria that are relevant to the mechanical performance of girth welds.

7.4. Possible Updates in Welding Procedure Qualification

Pipes selected for welding procedure qualification must represent the pipes on which the procedure would be applied. In the context of demonstrating adequate weld strength for a project, the pipes should be selected with high-end tensile strength and low-end hardenability. The qualification pipe should be tested, and its tensile properties and chemical composition should be recorded in qualification reports.

One alternative approach to demonstrate adequate weld strength is to conduct all-weld-metal tensile tests.

The overall weld quality can be checked by conducting cross-weld tensile tests. If the tests are not instrumented, failure outside the weld region could be recognized as the acceptance criteria, provided the pipe strength and chemical composition are properly selected and/or documented. Instrumented cross-weld tensile tests can be used to ensure welds achieve a target strain capacity, regardless of the eventual failure location of the specimens.

Qualification welds should be made with full considerations of the impact of cooling rate, often represented by heat input, on the weld metal strength and HAZ hardness. Slow cooling rates (high heat input) within expected ranges would produce low-strength weld metal and greater levels of HAZ softening, which would lead to a conservative outcome from the perspective of weld properties.

8. CONCLUDING REMARKS

Pipelines have had an excellent overall safety record. The recent increase in girth weld incidents in newly constructed pipelines is unexpected by historical trends. However, when analyzed in a greater depth, it is evident that there are systemic gaps in industry practice and standards which have allowed the technical contributors to the failures to exist. Fortunately, most constructed pipelines have integrity levels far exceeding those implied by the minimum requirements in industry standards. The information given in this paper demonstrates that some minimum requirements in the industry standards are not sufficient when real-world loading conditions are considered. More importantly, the “handover” of standards governing different phases of a pipeline’s life, from design, material

¹ The defect acceptance criteria in EPRG Guidelines, referenced in EN 12732, and AS 2885.2 are established with an expected minimum tensile strain capacity of 0.5% which is consistent with the proposed design requirements.

procurement, construction, to operation and maintenance, has gaps and inconsistencies. The proposed updates to a few relevant standards could be a starting point for updating the industry practice and standards.

CSA Z662 has more stringent requirements on the strength of on Annex K welds (typically mechanized welds) than many body welds (typically manual welds). One potential reason for the different strength requirements could be perceived maximum flaw allowance as manual welds are typically accepted by workmanship criteria whereas mechanized welds are frequently accepted by alternative flaw acceptance criteria, such as Annex K. However, such reasoning ignores two important factors. First, manual welds are more likely to be located in areas of higher stresses, such as tie-in locations. Secondly, flaw size only comes into play for weld integrity when welds (1) have low toughness and (2) do not experience high levels of strain concentration due to gross weld strength undermatching. Welds can fail at low strains in the absence of weld flaws if there is gross weld strength undermatching. When these factors are considered, it is difficult to justify that manual welds should have lower strength requirements than mechanized welds, unless these welds are expected to experience low longitudinal stresses, such as welds in stations. It is reasonable to suggest that the requirements and quality control for manual welds, such as weld strength mismatch and heat input, deserve extra attention.

9. ACKNOWLEDGEMENT

The content of this paper reflects the knowledge and data accumulated over many years while working with pipeline operators, regulators, and standards organizations. The support of pipeline operators, PRCI, US DOT PHMSA, and CER (the Canada Energy Regulator) is gratefully acknowledged. The authors are grateful for the support of Mr. Patrick Fleck, Mr. Alex Wang, and Mr. Paul Pianca in preparing this paper. The opinions expressed in this paper are of the authors, not their employer, funding organizations, or standards organizations that the authors participate.

REFERENCES

- 1 Wang, Y.-Y., Jia, D., and Rapp, S., "Robust Girth Welds Suitable for Realistic Field Conditions," presentation to the API 1104/5L Joint Task Group, January 21, 2020, Fort Worth, TX.
- 2 Chen, H., Feng, H., Chi, Q., and Huo, C., "Failure Analysis of a Stress-Based Pipeline under Plastic Strain," Pipeline Integrity Management under Geohazard Conditions, Paper No. AIM-PIMG2019-1028, M. Salama, Y.-Y. Wang, et al., Eds, ISBN: 978-07918-6199-8, ASME, New York, NY, 2020.
- 3 Van Hamat, W., Wan Ismail, W, Ibrahim, K., M Min, G, MD Aris, N., "High Strain Weld Solutions for Geohazard Active Environment," Pipeline Integrity Management under Geohazard Conditions, Paper No. AIM-PIMG2019-1068, M. Salama, Y.-Y. Wang, et al., Eds, ISBN: 978-07918-6199-8, ASME, New York, NY, 2020.
- 4 Nesbitt, J., Paviglianiti, J., "Girth Weld Area Strain-Induced Failures," presentation at the PHMSA RD Forum, February 19-20, 2020, Arlington, VA.
- 5 Wang, Y.-Y., Horsley, D, & Rapp, S. "Evolution of Linepipe Manufacturing and its Implications on Weld Properties and Pipeline Service." *Proceedings of the 2016 11th International Pipeline Conference. Volume 3: Operations, Monitoring and Maintenance; Materials and Joining*. Calgary, Alberta, Canada. September 26–30, 2016. V003T05A036. ASME. <https://doi.org/10.1115/IPC2016-64632>
- 6 Wang, Y.-Y., Rapp, S, Horsley, D, Warman, D, & Gianetto, J. "Attributes of Modern Linepipes and Their Implications on Girth Weld Strain Capacity." *Proceedings of the 2018 12th International Pipeline Conference. Volume 3: Operations, Monitoring, and Maintenance; Materials and Joining*. Calgary, Alberta, Canada. September 24–28, 2018. V003T05A030. ASME. <https://doi.org/10.1115/IPC2018-78809>

-
- 7 Wang, Y.-Y., *Girth Welding in the Age of Evolving Steel Manufacturing Processes and under Realistic Field Conditions*, presentation at API 1104 and API 5L meetings, January 22, 2019.
 - 8 Wang, Y.-Y., Jia, D, Warman, D, Johnson, DL, & Rapp, S. "Improved Linepipe Specifications and Welding Practice for Resilient Pipelines." *Proceedings of the 2020 13th International Pipeline Conference. Volume 3: Operations, Monitoring, and Maintenance; Materials and Joining*. Virtual, Online. September 28–30, 2020. V003T05A023. ASME. <https://doi.org/10.1115/IPC2020-9725>
 - 9 Wang, Y.-Y. and Jia, D., “Welding Options and Linepipe Specifications for Strain-Resistant Girth Welds,” PRCI Research Exchange Meeting, March 2020, San Diego, CA.
 - 10 Wang, Y.-Y. and Jia, D., “Interim Recommendations for the Mitigation of Low-Strain Girth Weld Failures,” report catalog number PR-350-174507-R03, March 2021. <https://www.prci.org/208477.aspx>
 - 11 Wang, Y.-Y, Liu, B., and Fleck P., “Strain-Based Design and Assessment of New and Ageing Pipelines,” Technology for Future and Ageing Pipelines, October 19-21, 2021, Gent, Belgium.
 - 12 Theriault, B., McKenzie-Johnson, A., Hart, J., and Paulsen, S., “Correlation of Single-Run ILI IMU Bending Strain Features to Geohazard Locations,” Pipeline Integrity Management under Geohazard Conditions, Paper No. AIMPIMG2019-1003, M. Salama, Y.-Y. Wang, et al., Eds, ISBN: 978-07918-6199-8, ASME, New York, NY, 2020.
 - 13 Mekalled, B. and Paviglianiti, J., “Impact of Geohazards on Pipelines and Regulatory Powers and Restrictions in Canada and the United States,” Pipeline Integrity Management under Geohazard Conditions, Paper No. AIMPIMG2019-1041, M. Salama, Y.-Y. Wang, et al., Eds, ISBN: 978-07918-6199-8, ASME, New York, NY, 2020.
 - 14 Knauf, G., G. Hohl, and F. M. Knoop. "The effect of specimen type on tensile test results and its implications for linepipe testing." *3 R INTERNATIONAL* 40, no. 10/11 (2001): 655-661.
 - 15 API 1104:2013 “Welding of Pipelines and Related Facilities,” 21st Edition
 - 16 CAN/CSA Z662-15 Oil and Gas Pipeline Systems, June 2015.
 - 17 BS EN 12732 Gas infrastructure - Welding steel pipework - Functional requirements, British Standards Institution, London, UK.
 - 18 Knauf, G. and Hopkins, P., “The EPRG Guidelines on the Assessment of Defects in Transmission Pipeline Girth Welds,” *3R International*, 35, 10/11, 1996, pp.660-4.
 - 19 Wang, Y.-Y., Liu, M., Gianetto, J., and Tyson, B., “Considerations of Linepipe and Girth Weld Tensile Properties for Strain-Based Design of Pipelines,” Proceedings of the 8th International Pipeline Conference, Paper No. IPC2010-31376, September 27 – October 1, 2010, Calgary, Alberta, Canada.
 - 20 Andrews, R., Denys, R., Knauf, G., and Zarea, M., “EPRG Guidelines on the Assessment of Defects in Transmission Pipeline Girth Welds – Revision 2014,” 2015
 - 21 AS/NZS 2885.2:2020 Pipeline – Gas and Liquid Petroleum, Part 2: Welding, Joint Australian/New Zealand Standard, May 29, 2020
 - 22 Liu, B, Wang, Y.-Y., Chen, X., and Warman, D., “Effects of Biaxial Loading on the Tensile Strain Capacity of Girth Welds with Weld Strength Undermatching and HAZ Softening,” Proceedings of the 13th International Pipeline Conference, Paper No. IPC2020-9663, September 28 – October 1, 2020, Calgary, AB, Canada.
 - 23 Denys, R. and Lefevre, T., “Effects of Welding on HAZ Softening of X70/X80 TMCP Linepipe Steels”, PRCI Contract PR-202-9635, January 2000.

-
- 24 Hamada, M., Hirata, H., Okaguchi, S., Shitamoto, H., Yamamoto, A., Takahashi, N., Miura, M., and Takeuchi, I., “Material Design for Line Pipe Steel to Minimize HAZ Softening and Obtain Good HAZ Toughness.” *International Journal of Offshore and Polar Engineering* 18, September 2008.
 - 25 Garcia, M., Lu, C., and Barbaro, F., “Evaluation of Weld Zone Hardness in the HAZ of Modern Pipeline Steels,” presentation at PRCI Virtual Research Exchange Meeting, March 2021.