JOINT INDUSTRY PROJECT (JIP)

FINAL SUMMARY REPORT

Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines

Prepared for:

American Steel Pipe
Arcelor Mittal
APA Group
Berg Pipe
Boardwalk Pipelines
Borusan Manessman
Cheniere
Dura-Bond Pipe
Enbridge
Energy Transfer
Enterprise Products
EVRAZ
Jindal Tubular
JSW Steel USA Inc.
Kinder Morgan
Marathon Pipe Line
PG&E
POSCO
SSAB
STUPP
TC Energy
Welspun Tubular
Williams

Technical Contributions from:

Microalloying International
CRES (Center for Reliable Energy Systems)
DNV GL
Dynamic Risk
ITI International
Microalloyed Steel Institute
Micro-Met International Ltd.

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Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines

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Signatures

Prepared for	**JIP Sponsor Committee**
Prepared by:	Signature
	Robin Gordon, PhD Project Leader, Microalloying International
Reviewed and Approved by:	Signature
	Steve Rapp P.E. JIP Chairman, Enbridge

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Foreword

This Joint Industry Project (JIP) was initiated to address several recent pipeline failures that have occurred at girth welds in pipelines that were constructed using API 5L X70 line pipe, and field welded using API 1104 qualified welding procedures. These failures occurred in pipelines that were designed using conventional stress-based design. Some of these failures occurred during hydrotest or shortly after the pipeline entered service. Since this project commenced, additional failures have occurred further highlighting the necessity to address this problem. Clearly something needs to change in order to eliminate future pipeline failures with similar attributes.

As described in this Summary Report, the role of girth weld undermatching, longitudinal pipe strength, heat affected zone softening, welding consumables, welding procedures, steel production, and pipe mill procedures are all considered to determine their influence on the tensile strain capacity of a pipeline girth weld and its ability to withstand supplemental longitudinal strain. As the failures are consistently characterized by girth weld undermatching (weld and/or HAZ) it is clear that, changes to current practices are needed to achieve girth weld overmatching to increase strain capacity. At a high level, this is accomplished by reducing the pipe longitudinal strength, increasing weld metal strength and limiting heat affected zone (HAZ) softening. The results from this JIP highlight the complexity of this problem and the complexity of producing generic guidelines. However, in order to eliminate future failures, all stakeholders (Operators, Steel Producers and Pipe Mills) need to adapt and make certain changes that materially mitigate future failures. Failure to make changes is not acceptable.

Although girth weld undermatching is clearly a contributing factor; changing welding consumables and welding procedures will not be effective as a single solution. In addition to girth weld overmatching Heat Affected Zone (HAZ) softening must also be addressed. As HAZ properties are largely a consequence of pipe chemistry and weld thermal cycles, careful consideration must be given to both the chemical composition of the steel and the welding Heat Input. Modern X-70 steel processing has advanced generationally, driven by the intent of enhanced weldability, fracture toughness, sour service resistance and Grade X80 and X100 development. These generational developments have produced significant changes in nominal chemical composition and steel processing over the years and, in some cases, has resulted in steels which exhibit increased levels of HAZ softening, which was unintentional.

The measurement of longitudinal tensile properties and establishing limits on Yield Strength and Tensile Strength are required to assure the design condition for weld joint overmatching. These requirements have been evaluated through finite element modeling and are presented in this report. This JIP provides a foundation to proactively increase the tensile strain capacity and mitigate future girth weld failures in modern X70 line pipe. This JIP does not provide a perfect solution that meets all needs and provides complete assurance from further failures. However, the recommendations provided represent interim guidance with respect to field welding and pipe purchase specifications that will greatly reduce the frequency of failures attributed to girth weld undermatching. Certain recommendations for future work, in addition to parallel research on this topic, will be required to further refine this interim guidance.

JIP Project Technical Team

The Joint Industry Project (JIP) Project Technical Team is responsible for finalizing the scope and deliverables, and execution of the Joint Industry Project "*Enhanced Girth Weld Performance for New Grade X70 Pipelines*". This report is the Summary Report presents the findings from the JIP Project Technical Team for use by the JIP Sponsors. The JIP Project Technical Team comprised:

- Robin Gordon, Principal Investigator — Microalloying International
- Yong-Yi Wang, Task Lead — CRES (Center for Reliable Energy Systems)
- Bill Bruce, Task Lead — DNV GL
- Malcolm Gray, Task Lead — Microalloyed Steel Institute
- Phil Kirkwood, Task Lead — Micro-Met International Ltd.
- Daniel Guzman, Project Manager — ITI International
- Patrick Vieth, Advisor — Dynamic Risk

The JIP Project Technical Team would like to acknowledge the following individuals for their Advisory contributions through the course of this project: Steve Rapp, Dave Horsley, Dave Warman, and David L. Johnson.

JIP Sponsor Representatives

This JIP has 23 sponsors. Each company designated one representative as the voice of their company. The JIP Sponsors (or JIP Sponsor Representatives) are:

- Steve Rapp, Chairman — Enbridge
- Jim Frost — American Steel Pipe
- Mehdi Fardi — APA Group
- Murali Manohar — Arcelor Mittal
- Frédéric Combaud — Berg Pipe
- Rodney Clayton — Boardwalk Pipelines
- Fatih Ozkan — Borusan USA
- Chris Williams — Cheniere
- Mark Anderson — Dura-Bond Pipe
- Dennise Loya — Energy Transfer
- Jake Haase — Enterprise Products
- Laurie Collins — EVRAZ
- Pepper Vance — Jindal Tubular
- Vickie Harthcock — JSW Steel USA Inc.
- F. Henry Martinez — Kinder Morgan
- Sara Maul — Marathon Pipe Line
- David Xu — PG&E
- Aidan (Yong Keun) Park — POSCO America
- Dan Edelman — SSAB
- Pankaj Mittal — STUPP
- Robert Lazor — TC Energy
- P.N. Mahida — Welspun Tubular
- Daniel Castro — Williams

Appendix A contains the guidelines for engagement for the JIP execution.

Executive Summary

Introduction

Over the last 10 years, a number of girth weld failures have occurred in Grade X70 cross-country pipelines constructed using modern thermo-mechanically controlled process (TMCP) steel. These failures occurred during hydrotesting or after the pipeline entered service. In some cases, the failures occurred shortly after the pipeline entered service. Most of these failures occurred at nominal strain levels less than 0.5% (i.e., within the limits of conventional stress-based design).

A Joint Industry Project (JIP) was launched in March 2017 to determine the underlying cause of these failures and develop guidelines to mitigate low strain failures in new Grade X70 pipelines.

The JIP was performed in three major phases:

1. Phase 1

   Review of Pipeline Failures, Relevant Literature and Development of Preliminary Guidelines.

2. Phase 2

   Experimental Test Program and Supplementary Finite Element Analysis.

3. Phase 3

   Best Practice Guidelines and Performance Requirements.

This report presents the recommendations developed from the JIP to mitigate low strain failures at Grade X70 girth welds.

Girth Weld Failures

In Phase 1 of the JIP, six girth weld failures were reviewed. This comprised a review of failure analysis reports prepared by/for associated pipeline companies and, in some cases, independent failure analysis performed by CRES. The primary purpose of the failure analysis reports was to demonstrate code compliance, as opposed to performing a detailed failure analysis. As a result, several of the failure analysis reports did not include extensive pipe and girth weld testing to fully characterize the pipe material and girth weld properties.

Three of the six girth weld failures were in-service ruptures. One of the failures was an in-service leak. The two remaining failures were hydrostatic test leaks. Four of the six failures occurred on Grade X70 pipelines. One failure occurred on a Grade X52 pipeline. The remaining failure occurred at a Grade X70 to X80 transition weld with different pipe wall thicknesses (WTs) on either side of the weld.

All the girth weld failures occurred in manual welds in helically submerged arc-welded pipe (SAWH) or electric resistance weld (ERW) pipe:

- Three failures occurred due to girth weld under-matching that, in some cases, was exacerbated by heat-affected zone (HAZ) softening;
- One failure occurred at an under-matched transition girth weld in which the heavier wall pipe was tapered at the pipe end, i.e., it was not counter-bored. The transition girth weld geometry will have produced a large Stress Concentration Factor (SCF) at the transition girth weld and further increased the strain in the under-matched girth weld and softened HAZ.
- One failure which resulted in a leak during hydrotest occurred at an under-matched girth weld that contained a hydrogen crack at a repair weld; and,

- One failure occurred in a girth weld, which contained a small thumbnail flaw (1.5 x 10 mm). This failure occurred through the pipe body / HAZ. The reason for this failure is not fully understood and will be further evaluated. Note, this flaw was within the normal workmanship criteria of API 1104 and was therefore compliant with API 1104.

Of the six girth weld failures only one girth weld (which contained a hydrogen crack), did not meet the requirements of API 1104. Although this girth weld passed x-ray inspection it did contain a crack which is not permitted by Code. The remaining girth welds did reportedly meet the requirements of API 1104 (i.e., any flaws that were detected were within the normal workmanship flaw acceptance criteria). The transition girth weld was fabricated in compliance with Appendix I of ASME B31.8.

The three failures that are most concerning are those where failure occurred in nominally sound Grade X70 girth welds that were fabricated using:

- Pipe that was compliant with American Petroleum Institute (API) 5L; and,
- Weld procedures that met the requirements of API 1104.

The main contributing factors to the three failures in nominally-sound girth welds were girth weld under-matching and HAZ softening, confirming that guidelines to mitigate low strain failures in girth welds should focus on these two factors.

Based on the major findings from Phase 1 of the JIP, Phase 2 of the JIP was structured to develop data that would enable the development of Guidelines to Mitigate Low Strain Girth Weld Failures. The Guidelines have three components:

1. Control pipe longitudinal tensile properties to facilitate girth weld over-matching;
2. Implement improved girth welding practices (processes and procedures) that produce over-matched girth welds. Further, include additional weld procedure qualification (WPQ) requirements to ensure over-matched girth welds; and,
3. Develop guardrails to minimize/control girth weld HAZ softening.

Pipe Tensile Properties

To facilitate girth weld over-matching in Grade X70 pipelines it is recommended that the following supplementary longitudinal tensile property requirements are specified for new Grade X70 pipe orders (SAWL, SAWH and HF-ERW):

1. Longitudinal tensile tests should be performed during manufacturing pre-production qualification testing (MPQT) and pipe production at the same frequency as transverse tensile tests to establish a full distribution of longitudinal tensile properties;
2. The longitudinal tensile tests should be performed on full thickness strap specimens;
3. The longitudinal tensile properties should fall within the following ranges:
   - YS-L = SMYS to SMYS + 17 ksi (120 MPa); and,
   - TS-L = SMTS to SMTS + 17 ksi (120 MPa).
4. The re-test provisions for longitudinal tensile tests should be the same as transverse tensile tests.

Although these requirements have been successfully applied in several recent major pipeline projects in which SAWH pipe was made at two different pipe mills, several steel producers and pipe mills have indicated that they will not be able to meet the 17 ksi cap requirement on YS-L and TS-L for SAWH and HF-ERW pipe with their current manufacturing capabilities. This in part is due to a) the current method of measuring transverse tensile properties in pipe using flattened strap specimens which tends to report lower values of yield strength due to the Bauschinger effect and b) concerns regarding under strength pipe. Both of these factors have caused Pipe Mills to over-specify tensile properties in plate or coil to provide a margin that allows for a reduction in the transverse yield strength in pipe as measured using flattened strap specimens. Although transverse tensile properties in pipe are generally measured using flattened strap specimens there are other tensile specimen designs that could be adopted to address this issue, e.g., round bar specimens or ring expansion tests, both of which are permitted by API 5L.

Girth Welding

To facilitate girth weld over-matching in Grade X70 pipelines, the Project Technical Team proposes the following girth welding recommendations for shielded metal arc welding (SMAW) and SMAW/FCAW girth welds:

1. For new major Grade X70 pipeline projects it is recommended that girth weld procedures are qualified on Project Pipe and ideally on pipe with longitudinal tensile properties that are at the upper range (e.g., >95%) of the pipe order. In addition, consideration should be given, where practical, to performing WPQ on pipe that has been subjected to a fusion-bonded epoxy (FBE) thermal cycle to account for aging. If pre-existing weld procedures are used without re-qualification on project pipe, then girth weld over-matching must be ensured. This can be achieved by performing All Weld Tensile (AWT) tests to measure weld metal tensile properties to demonstrate that the measured weld metal tensile properties (YS and TS) exceed the maximum pipe longitudinal tensile properties after FBE coating;
2. Cross-weld tensile (CWT) tests should be performed on specimens with the weld reinforcement in place;
3. CWT specimens should fail in the base pipe (i.e., failure in the girth weld or HAZ is not acceptable). In cases where CWT specimens fail in the weld region but after significant deformation occurs in the parent pipe (i.e., gross section yielding occurs in the parent pipe), the suitability of the weld procedure can be assessed on a case-by-case basis;
4. Mainline pipe-to-pipe, or tie-in girth welds should be made using SMAW low-hydrogen vertical down (LHVD) – e.g., E9045 or E10045 – or gas shielded flux-cored arc welding (FCAW-G) – e.g., E91 T1, E100 T1, etc. – consumables for the fill-and-cap passes. Although the weld root has historically been made using E6010 consumables, the use of E8010 for the weld root should be encouraged – particularly for thin wall pipe. Note, where possible mechanized FCAW-G should be used in preference to manual FCAW-G. If manual FCAW-G is used careful control of the heat input is required.;
5. There are cases where the increased flexibility of an all-cellulosic SMAW girth weld provides clear benefits. However, the Project Technical Team recommends that SMAW procedures using E6010 or E8010 (for the root/hot pass) and E8010 (for the fill-and-cap passes) should be limited to short pipeline replacement sections in non-geohazard areas, pipe assemblies and station piping. In cases where all-cellulosic girth weld procedures are employed consideration should be given to qualifying weld procedures with enhanced weld cap heights and weld cap widths.
6. Transition welds between pipes of the same grade but different wall thicknesses should be made using pipe that is counter-bored so that the pipe on either side of the girth weld is the same thickness. This will eliminate the SCF due to wall thickness difference either side of the girth weld.

7. For transition welds between pipes of different grades and wall thickness, it is necessary to follow the guidance given in Appendix I of ASME B31.8 (or similar guidance given in B31.4) which calls for an internal taper between 14 and 30 degrees. If you counterbore the lower strength material, the thinner material on the lower strength (counter-bored) side will be under-designed for hoop strength.
8. The degree of HAZ softening and the width of the softened HAZ are very dependent on weld heat input, so limits should be placed on the maximum heat input. A maximum heat input of 1.0 - 1.5 kJ/mm is proposed for SMAW and SMAW/FCAW girth welds. This is particularly important for thinner wall pipe where the HAZ may be a significant proportion of the pipe wall thickness. For heavier wall pipe an increased Heat Input may be considered provided it is qualified. Monitoring electrode run-out length can be used to monitor SMAW heat input during construction.

HAZ Softening

It was originally hoped that the results from the Bead on Pipe and Girth Weld Test programs would enable the development of guidelines to mitigate HAZ softening in Grade X70 pipe.

Although the bead on pipe (BOP) test results indicate that HAZ softening susceptibility increases as Pcm decreases, the steels tested did not cover the entire range of Grade X70 alloy designs and, in particular, did not include steels with optimal variation in Pcm, (i.e., low carbon steels with significant alloy additions to help promote strength). In addition, there is concern that the BOP results may have been influenced by the WT variation of the BOP samples, which ranged in thickness from 0.340 to 0.689 in. The hardness results from the girth weld tests also exhibit significant scatter, with no obvious trends. Thus, no firm recommendations can be made on steel composition limits to mitigate HAZ softening without additional testing. Nevertheless, it seems logical that the pipe materials that may represent the highest potential to HAZ softening are lean alloy (low Pcm) steels where the steel derives a significant proportion of its strength from aggressive water cooling in the later stages of TMCP processing.

Both the degree of HAZ softening and the width of the softened HAZ are very dependent on weld heat input, so limits should be placed on the maximum heat input. A maximum heat input of 1.0 - 1.5 kJ/mm is proposed for SMAW/FCAW girth welds. In addition, although the BOP results did not permit the development of firm recommendations on steel chemical composition, they did indicate that HAZ softening susceptibility increases as Pcm decreases. As a result, specifying a minimum Pcm (e.g., a Pcm >0.14) may also help mitigate HAZ softening.

Girth Welds that Require Special Consideration

SMAW girth welds in thin wall Grade X70 pipelines (e.g., <0.375") present challenges since the root pass and hot pass represent a significant proportion of the pipe wall thickness. As a result, even in cases where the fill-and-cap passes are made with SMAW LHVD consumables, it is difficult to produce a matching or over-matching girth weld. This is particularly true if the root and hot pass are deposited with an E6010 SMAW consumable. Even in cases where the root and hot pass are deposited with an E8010 SMAW consumable there is still the potential for an under-matched girth weld. An alternative option for operators who are considering a thin wall Grade X70 pipeline design is to replace the thin wall Grade X70 pipe with either Grade X65 or Grade X60 pipeline.

Switching from Grade X70 to Grade X65 or X60 pipeline provides the following benefits for thin wall pipelines:

1. The equivalent Grade X65 or Grade X60 pipeline designs will require pipe with an increased wall thickness which, in turn, means that the proportion of the girth weld associated with the root and hot pass will decrease; and,
2. A reduction in pipe grade (and pipe strength) will facilitate girth weld over-matching using an E8010 consumable for the weld root and hot pass.

If Grade X65 or X60 pipe is used the same limits on YS-L and TS-L should be applied (i.e., the maximum YS-L and TS-L should not be more than 17 ksi [120 MPa] above the specified minimum tensile properties).

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1 Introduction

Over the last 10 years, a number of girth weld failures have occurred in Grade X70 cross-country pipelines constructed using modern thermo-mechanically controlled process (TMCP) steel. These failures occurred during hydrotesting or after the pipeline entered service. In some cases, the failures occurred shortly after the pipeline entered service. The failures occurred at nominal strain levels less than 0.5% (i.e., within the limits of conventional stress-based design).

A Joint Industry Project (JIP) was launched in March 2017 to determine the underlying cause of these failures and develop guidelines to mitigate low strain failures in new Grade X70 pipelines.

The JIP comprised three major phases:

- Phase 1

  Review of Pipeline Failures and Relevant Literature and Development of Preliminary Guidelines.

- Phase 2

  Experimental Test Program and Supplementary Finite Element Analysis.

- Phase 3

  Best Practice Guidelines and Performance Requirements.

This report presents the Best Practice Guidelines to mitigate low strain failures at Grade X70 pipeline girth welds.

2 Scope of JIP

2.1 General

The JIP was initiated in June 2017 by the Project Technical Team, with the following objectives:

- Determine the root cause of recent girth weld failures in Grade X70 pipelines; and,
- Develop guidelines to mitigate low strain girth weld failures in new Grade X70 pipelines.

The JIP comprised three phases:

- Phase 1

  Review of Recent Grade X70 Girth Failures, Review of Relevant Literature & Development of Preliminary Guidelines based on Current Knowledge.

- Phase 2

  Experimental Test Program and Supplementary Finite Element Analysis.

- Phase 3

  Summary Report including Best Practice Guidelines and Performance Requirements to Mitigate Low Strain Girth Weld Failures.

This Draft Final Report is the *Phase 3 Summary Report*.

2.2 Phase 1

Table 1 summarizes JIP Phase 1 tasks.

Table 1. Phase 1 Task Summary

Task	Description	Task Leader
1	Review of Recent Pipeline Girth Weld Failures	YYW
2	Review of Grade X70 pipe manufacturing methods.	JMG
3	Review of Metallurgical Work on HAZ Softening.	PK
4	Review of Under-matching/HAZ Softening	YYW
5	Development of Preliminary Guidelines	RG
6	Development of Phase 2 Workplan	RG

Notes:
JMG: Dr. Malcolm Gray, Microalloyed Steel Institute
PK: Dr. Phil Kirkwood, Micro-Met International
RG: Dr. Robin Gordon, Microalloying International
YYW: Dr. Yong-Yi Wang, Center for Reliable Energy Systems (CRES)
Task reports were prepared and distributed to JIP Sponsors, which detailed the work that was performed under each task.

2.3 Phase 2

Table 2 summarizes JIP Phase 2 tasks.

Table 2. Phase 2 Task Summary

Task	Description	Task Leader
1	Development of Grade X70 Database	RG
2	Grade X70 SMAW Girth Weld Procedure Qualification Database	RG
3	Tensile Strain Capacity Analysis (FEA)	YYW
4	Girth Weld Test Program	RG
5	Bead on Pipe Tests to Evaluate HAZ Softening	RG
6	Alternative SMAW Girth Welding Options	BB
Notes: BB: Mr. Bill Bruce, DNV-GL Task reports were prepared and distributed to JIP Sponsors, which detailed the work that was performed under each task.		

2.4 Phase 3

Phase 3 of the JIP comprised two tasks:

1. Summarize the work performed in the JIP (phases 1 and 2); and,
2. Based on this work (see Item 1), develop guidelines to mitigate low strain failures in Grade X70 pipeline girth welds.

2.5 Project Management

In an effort to ensure transparency into this work product and associated guidelines, each JIP Sponsor has been provided the opportunity to provide a 2-page letter to present certain views related to their perspectives. These letters are provided in Appendix B.

3 Abbreviations and Glossary

Table 3 lists and provides meanings for abbreviations used in this Draft Final Report.

Table 4 defines terms and phrases used in this Draft Final Report.

Table 3. Abbreviations

Abbreviation	Meaning
~	Approximately
°	Degree
API	*American Petroleum Institute*
AWS	*American Welding Society*
AWT	All weld metal tensile
BOP	Bead on pipe (test)
CE	Carbon equivalent
CFR	Code of Federal Regulations
CMT	(Fronius) Controlled metal transfer
CGHAZ	Coarse grain heat affected zZone
Cr	Chromium
CRES	Center for Reliable Energy Systems
Cu	Copper
CWT	Cross-weld tensile
DMC	Design, Materials & Construction
e.g.	For example
EAF	Electric arc furnace
ECA	Engineering Critical Assessment
ERW	Electric Resistance Weld
etc.	Et cetera
FBE	Fusion-bonded epoxy
FCAW	Flux-cored arc welding
FCAW-G	Gas Shielded FCAW
FEA	Finite Element Analysis
GMAW	Gas metal arc welding
HAZ	Heat-affected zone
HF-ERW	High Frequency Electric Resistance Welded pipe
HV	Vickers Hardness
HV_{10}	Vickers Hardness using a 10 kg load
i.e.	That is
ID	Internal diameter
IIW	*International Institute of Welding*

Abbreviation	Meaning
Inc.	Incorporated
JIP	Joint Industry Project
kg	Kilogram
kJ	Kilojoule
ksi	One thousand pounds per square inch
LH	Low hydrogen
LHVD	Low-hydrogen vertical down
max.	Maximum
min.	Minimum
mm	Millimeter
MPa	Mega Pascal
MPQT	Manufacturing pre-qualification test (program)
MPS	Manufacturing procedure specifications
Ni	Nickel
OD	Outside diameter
OLAC	On-line accelerated cooling
PHMSA	Pipeline and Hazardous Materials Safety Administration
ppm	Parts per million
PRCI	*Pipeline Research Council International*
PSL2	Product Specification Level 2 (API 5L)
PWHT	Post weld heat treatment
Rev.	Revision
RMD	(Miller) Regulated Metal Deposition
ROW	Right-of-way
RST	Reduced section tensile
SAW	Submerged arc weld
SAWH	Helically submerged arc-welded pipe
SAWL	Longitudinally submerged arc welded pipe
SCF	Stress concentration factor
SMAW	Shielded metal arc welding
SMTS	Specified minimum tensile strength
SMYS	Specified minimum yield strength
SSFCAW	Self-shielded flux-cored arc welding
STT	(Lincoln) Surface tension transfer
TMCP	Thermo-mechanically controlled process
TS	Tensile strength
TSC	Tensile strain capacity
TS-L	Tensile strength – longitudinal direction

Abbreviation	Meaning
TS-T	Tensile strength – transverse direction
US	United States
USA	United States of America
vs.	Versus
WPQ	Welder performance qualification
WT	Wall thickness
X70	API 5L Grade X70 pipe
Y/T	Yield (yield strength) to tensile (tensile strength) ratio
YS	Yield strength
YS-L	Yield strength – longitudinal direction
YS-T	Yield strength – transverse direction

Table 4. Glossary

Abbreviation	Meaning
API 1104	*API 1104* is the *American Petroleum Institute* standard for Welding Pipelines and Related Facilities.
API 5L	*API 5L* is the *American Petroleum Institute* specification for line pipe.
Over-match	*Over-match* occurs when the weld metal is stronger than the base pipe material. See also, *under-match*.
P_{cm}	*Pcm* is a chemical composition parameter used to mitigate hydrogen cracking.
$t_{8/5}$	$t_{8/5}$ is the time (t) it takes to cool material from 800 to 500°C.
Under-match	*Under-match* occurs when the base pipe material is stronger than the weld metal. See also, *over-match*.

4 Strain Capacity of Girth Welds

4.1 Weld Strength

The strength and strain capacity of a girth weld is dependent on a number of factors, including:

- Pipe strength;
- Weld metal strength; and,
- Heat-affected zone (HAZ) strength.

When developing a girth weld procedure, it is normal practice to select a welding consumable that will produce weld metal that is as strong, or stronger, than the base pipe material. When the weld metal is stronger than the base pipe material, the weld metal is said to over-match the (base) pipe material. Conversely, if the weld metal is weaker than the base pipe material, the weld metal is said to under-match the (base) pipe material.

The advantage of a girth weld that over-matches the longitudinal pipe tensile properties is that, should the pipe experience high strains during installation or operation, the strain will be distributed (e.g., transferred) into the pipe material instead of being focused in the girth weld. If the girth weld under-matches the longitudinal tensile properties of the pipe material, the strain will focus in the girth weld, resulting in high local strain and an increased risk of failure – even where the applied nominal strain in the pipeline is relatively low (e.g., <0.50% strain).

Although the terms under-matching and over-matching can be applied to either the yield strength or tensile strength of the pipe material it has become more common to base the degree of under / over-match as a function of the pipe tensile strength, since in the limit (i.e., high applied strain) it is the pipe tensile strength that is most important.

There is currently no requirement in *American Petroleum Institute* (API) 1104[(1)] (including Annex A) or *Canadian Standards Association* (CSA) Z662[(2)] for the measured tensile strength across the weld to be greater than the actual tensile strength of the pipe material. Cross-weld tensile (CWT) specimens can break in the weld provided they do so above the specified minimum tensile strength (SMTS) of the pipe material.

Figure 1 presents stress-strain curves that illustrate weld metal over-match and under-match. The stress-strain curve for the Grade X70 pipe material is based on specified minimum tensile properties. Weld metal stress-strain curves are presented for these cases:

- 20% Over-match;
- 10% Over-match;
- 10% Under-match; and,
- 20% Under-match.

At an applied strain that corresponds to a stress of 70 ksi (SMYS), the strain in the 10% under-matched weld is approximately three times larger than the strain in the pipe (see Figure 1). This highlights that under-matched girth welds will tend to focus strain in the girth weld instead of distributing or shedding the strain into surrounding pipe material. If the weld is under-matched by 20%, the strain in the weld metal is unbounded at a stress of 70 ksi. Conversely, for a 10% over-matched girth weld the strain in the weld is less than 0.5% for a global strain of 1% in the pipe, i.e., the strain is distributed (transferred) into the pipe material as opposed to the weld.

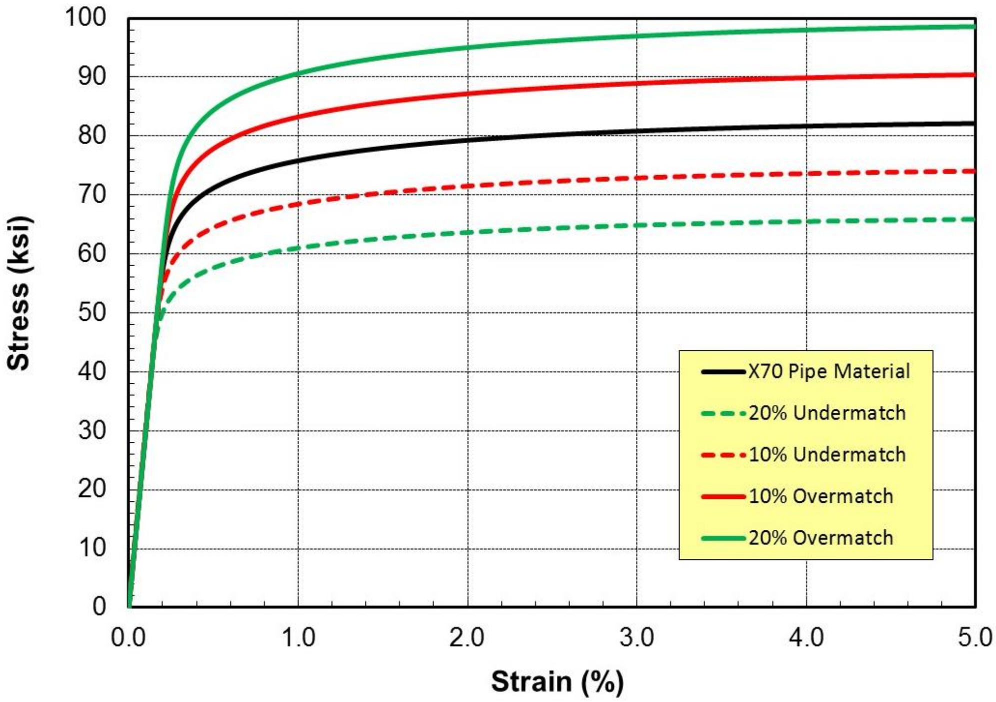


Figure 1. Schematic Stress-Strain Curves Showing Weld Metal Under-Matching and Over-Matching

TMCP steel and pipe has been produced for over 40 years. In recent years some suppliers have modified their practices to replace alloy content with very rapid accelerated cooling after rolling. The adoption of accelerated cooling has changed the shape of Grade X70 stress-strain curves over the last 20 years, with modern Grade X70 pipe exhibiting less strain hardening (higher Y/T) than older generation Grade X70 pipe. As the level of work hardening decreases (i.e., increased Y/T), the effect of under-matching becomes more even more significant.

It is worth noting that the average longitudinal Y/T ratio of Grade X70 pipe is in the range 0.85 – 0.90. In comparison the Y/T ratio of weld metal as determined from All Weld Tensile (AWT) tests is normally ≤ 0.80. As a result, even if the girth weld matches the strength of the parent pipe based on Tensile Strength yielding will initiate in the lower YS weld metal.

There are practical limits for the strength of weld metal deposited using cellulosic-coated shielded metal arc welding (SMAW) electrodes due to the risk of hydrogen-assisted cold cracking in the weld metal. To achieve higher strength, alloying additions in the weld metal must be increased, which tends to produce weld metal microstructures that may be susceptible to cold cracking (i.e., hydrogen cracking). When combined with the high levels of hydrogen in the weld that are produced by the use of cellulosic-coated electrodes, a relatively high risk of hydrogen cracking results.

Gas metal arc welding (GMAW) is a low-hydrogen welding process. Hence, girth welds made using mechanized GMAW are resistant to hydrogen cracking – even when the strength of the as-deposited weld metal is high. Flux-cored arc welding (FCAW) and SMAW can both be low-hydrogen welding processes provided an appropriate welding consumable and welding procedures are used.

4.2 HAZ Strength

The thermal cycles associated with welding result in the formation of a Heat Affect Zone (HAZ) in the parent pipe at the weld fusion line. The strength of the material in the HAZ region varies and can be higher and lower than the nominal pipe tensile properties. In general, there is a portion of the HAZ where the strength (and hardness) is lower than the nominal pipe. This region is referred to as the HAZ softened region. The width of the HAZ softened region and the extent of HAZ softening in a girth weld are dependent on a number of factors, including:

- Chemical composition of the steel;
- Original steel manufacturing process (e.g., TMCP parameters, rolling practice, cooling rates, etc.);
- Pipe forming strains (contributing to strain aging);
- Girth welding parameters – in particular: heat input; and,
- HAZ cooling rate, which is a function of heat input and pipe wall thickness.

If the pipe girth weld HAZ exhibits significant softening and the width of the HAZ is wide in comparison to the pipe wall thickness (WT), there is a risk that high strains can develop in the HAZ that may lead to failure of the girth weld. Since shear bands form at an angle of 45°, failures from HAZ softening are more likely to occur in SMAW or FCAW girth welds with wide bevel angles, instead of mechanized GMAW welds that tend to have near-vertical sidewalls.

Mechanized GMAW girth welds have near-vertical sidewalls, narrower HAZs (due to lower heat input), and are much less sensitive to HAZ softening than other girth welds. In addition, as the width of the HAZ gets narrower, the strength of the HAZ is improved due to contact strengthening where the deformation in the narrow HAZ band is restrained by the surrounding material. This phenomenon is the underlying reason why brazed joints have good strength, despite the low tensile strength of the braze material.

4.3 Pipe Material Strength

In late 2008, several large diameter gas transmission pipelines experienced field hydrostatic test failures or excessively expanded pipe joints following field hydrotesting. Subsequent metallurgical, mechanical and chemical composition tests confirmed that some pipe joints did not meet the specified minimum yield strength (SMYS), tensile strength and/or chemical composition requirements of API 5L, 43rd Edition(3).

These incidents led to:

- Extensive test programs to:
  - Characterize the tensile properties of higher grade line pipe; and,
  - Evaluate the test methods that measure transverse pipe tensile properties.
- The Pipeline and Hazardous Materials Safety Administration's (PHMSA's) *Advisory Notice*(4), which advises pipeline system owners and operators of the potential for high grade line pipe, installed on projects, to exhibit inconsistent chemical and mechanical properties.

The extensive test programs to characterize pipe tensile properties confirmed that the testing practices, testing procedures or both, used by different test companies, produced inconsistent results and revealed large variability in measured tensile properties, particularly the pipe transverse yield strength (YS-T). The variation in tensile results was associated with the procedures and methods of flattening and testing transverse strap specimens. During flattening of the straps, the specimens can experience a reduction in apparent yield strength from the Bauschinger effect. The reduction in apparent YS-T from the Bauschinger effect can result in pipe mills producing pipe with a YS-T that is higher than needed to compensate for potential reduction in the measured YS-T due to testing practices (Bauschinger effect). The aim of increased YS-T will also lead to pipe with higher-than-needed longitudinal pipe properties. Although the standard method of measuring transverse tensile properties in pipe uses flattened strap specimens there are other tensile specimen designs that could be adopted to address this issue, e.g., round bar specimens or ring expansion tests, both of which are permitted by API 5L

It is recognized that the development of improved test methods to measure transverse tensile properties in pipe would reduce the need for steel producers and pipe mills to over specify plate or coil tensile properties to account for the reduction in YS-T in pipe due to the Bauschinger effect. This would also reduce the longitudinal pipe properties and help facilitate girth weld overmatching. The development of improved test methods to measure transverse tensile properties in pipe is a topic of ongoing research and is outside the scope of this JIP.

In addition to pipe mills aiming for higher strengths to allow for the Bauschinger effect, one of the collateral impacts of the PHMSA advisory on low and variable yield strength pipe was for users to specify mill hydrostatic tests to 100% of SMYS, usually allowing for end loads, with no pipe body deformation. To meet this requirement, pipe mills typically increased their target strengths even further.

Due to concerns with under-strength pipe, many operators have included additional requirements in their line pipe specifications regarding transverse tensile testing. For example, many operators specify that:

> *If one pipe fails to meet the specified minimum yield strength +2 ksi in the hoop (transverse) direction, two additional pipes from the same heat and same test unit must also be tested and meet the API minimum yield strength. If one or both of the re-tests do not meet the minimum specified yield strength in the hoop (transverse) direction each pipe in the heat must be tested before it will be accepted.*

To address concerns regarding under-strength line pipe and to meet the common 2 ksi cushion, many pipe mills increased their target for YS-T – resulting in a trend to produce pipe with increased as-received YS-T. Although longitudinal and transverse tensile properties are not necessarily the same, any increase in YS-T is likely to manifest itself with a similar increase in longitudinal yield strength. This can lead to the need for higher-strength welding consumables to ensure girth weld over-match.

In addition to concerns regarding under-strength pipe there has been an increase, over the last 20 years, in the number of pipelines constructed using SAWH pipe as opposed to SAWL pipe. As discussed in Section 6, SAWH pipe exhibits higher longitudinal tensile properties than SAWL pipe. This has also contributed to an increase in typical longitudinal tensile properties for X70 pipe.

In summary, the PHMSA *Advisory Notice* and the associated concerns about under-strength pipe and testing practices, and increased hydrotest requirements resulted in pipe mills increasing the aim strength of Grade X70 pipeline (YS-T and TS-T) well above the specified minimum values.

5 Review of Pipeline Girth weld Failures

5.1 General

In Phase 1 of the JIP failure analysis, reports of six girth weld failures were reviewed. The reports were prepared by/for associated pipeline companies. The primary purpose of the failure analysis reports was to demonstrate code compliance, as opposed to performing a detailed failure analysis with extensive pipe and girth weld testing, to fully characterize the pipe material and girth welds.

Four of the six girth weld failures were in-service failures and two were hydrostatic test failures. Four of the six failures occurred on Grade X70 pipelines. One failure occurred on a Grade X52 pipeline. The remaining failure occurred at a Grade X70 to X80 transition weld with different pipe WTs on either side of the weld.

All the girth weld failures occurred in manual welds in helically submerged arc-welded pipe (SAWH) or high frequency electric resistance weld (HFERW) pipe.

Table 5 summarizes the details of the girth weld failures. Find full details of the failures in the *Phase 1 Task 1 Report*.

Table 5. Details of Pipeline Failures

<table>
<tr><th>Failure</th><th>Pipe Grade</th><th>Diameter (in.)</th><th>Wall (in.)</th><th>Wall (mm)</th><th>Type</th><th>Type of Girth Weld</th></tr>
<tr><td>1</td><td>X70</td><td>20</td><td>0.312</td><td>7.92</td><td>ERW</td><td>Pipe-to-pipe</td></tr>
<tr><td rowspan="2">2</td><td>X70</td><td>30+</td><td>0.740</td><td>18.80</td><td>SAWH</td><td rowspan="2">Transition weld</td></tr>
<tr><td>X80</td><td>30</td><td>0.360</td><td>12.34</td><td>SAWH</td></tr>
<tr><td>3</td><td>X52</td><td>12.75</td><td>0.250</td><td>6.35</td><td>ERW</td><td>Pipe-to-pipe</td></tr>
<tr><td>4</td><td>X70M</td><td>30</td><td>0.430</td><td>10.90</td><td>SAWH</td><td>Pipe-to-pipe</td></tr>
<tr><td>5</td><td>X70M</td><td>30</td><td>0.515</td><td>13.08</td><td>SAWH</td><td>Pipe-to-pipe</td></tr>
<tr><td>6</td><td>X70M</td><td>42</td><td>0.550</td><td>13.97</td><td>SAWH</td><td>Pipe-to-pipe</td></tr>
</table>

As part of Phase 2 of the JIP, the Grade X70 pipeline girth weld failures reported in Phase 1 of the JIP were reviewed again with the benefit of the results and knowledge gained during Phase 2 of the JIP. The Project Technical Team attempted to identify the primary cause of failure in each incident. This was not always straight-forward; in several cases, there were multiple factors that contributed to failure. Table 6 summarizes the girth weld failures and the minimum carbon (%) and Pcm values for the pipe materials.

Table 6. Girth Weld Failures

Failure	Pipe Grade	Dia (inch)	Wall (mm)	Pipe Type	Weld	Weld Process	Min Carbon	Min Pcm
1	X70	20	7.92	ERW	Pipe to Pipe	SMAW	0.038	0.127
2	X70 / X80	30	12.34 / 18.80	SAWH / SAWH	Transition (X70 / X80)	SMAW / FCAW	0.040	0.185
3	X52	12.75	6.35	ERW	Pipe to Pipe	SMAW	0.060	0.124
4	X70M	30	10.90	SAWH	Pipe to Pipe	SMAW	0.040	0.138
5	X70M	30	13.08	SAWH	Pipe to Pipe	SMAW	0.050	0.156
6	X70M	42	13.97	SAWH	Pipe to Pipe	SMAW	0.040	0.165

Of the six failures:

- Three failures (incidents 1, 5, and 6) occurred at pipe to pipe girth welds due to girth weld under-matching, in some cases, this was exacerbated by HAZ softening;
- One failure (Incident 2) occurred at an under-matched transition girth weld in which the heavier wall pipe was tapered at the pipe end, i.e., it was not counter-bored. The transition girth weld geometry will have produced a large SCF at the transition girth weld and further increased the strain in the under-matched girth weld and softened HAZ;
- One failure (Incident 3) occurred in a girth weld, which contained a small thumbnail flaw (1.5 x 10 mm). This failure occurred through the pipe body / HAZ. The reason for this failure is not fully understood and will be further evaluated. Note, this flaw was within the normal workmanship criteria of API 1104 and was therefore compliant with API 1104; and,
- One failure (Incident 4), which resulted in a leak during hydrotest, occurred at an under-matched girth weld that contained a hydrogen crack at a repair weld.

Of the six girth weld failures only one girth weld (which contained a hydrogen crack at a repair weld), did not meet the requirements of API 1104. Although this girth weld passed x-ray inspection it did contain a crack which is not permitted by Code. The remaining girth welds did reportedly meet the requirements of API 1104 (i.e., any flaws that were detected were within the normal workmanship flaw acceptance criteria). The transition girth weld was fabricated in compliance with Appendix I of ASME B31.8.

The three failures that are most concerning are incidents 1, 5, and 6, where failure occurred in nominally sound Grade X70 girth welds that were fabricated using:

- Pipe that was compliant with API 5L;
- Weld procedures that met the requirements of API 1104; and,
- Girth welds that did not contain flaws that may have contributed to the failure.

The main contributing factors to incidents 1, 5, and 6 were girth weld under-matching and HAZ softening, confirming that guidelines to mitigate low strain failures in girth welds should focus on these two factors. Although some of the girth welds contained small levels of High-Low misalignment this was within Code limits and was not considered to be a significant contributing factor to the failures.

All the girth weld failures occurred in girth welds that under-matched the surrounding pipe material. Detailed hardness mapping was performed in four of the six incidents (incidents 1, 2, 4 and 5) to characterize the hardness of the girth weld, HAZ and parent pipe. There is no hardness data for Incident 6 since the girth weld experienced fire damage. The hardness results confirmed the levels of girth weld under-match (based on girth weld hardness vs. average pipe hardness) and HAZ softening (minimum HAZ hardness vs. average pipe hardness) shown in Table 7.

Table 7. Girth Weld Under-Match and HAZ Softening in Incidents 1, 2, 4, and 5

Incident	Pipe Grade	Average Weld Metal Under-match		HAZ Softening (%)
		Fill & Cap (%)	Weld Root (%)	
1	X70	11	24	28
2	X70	0	12	16
4	X70	9	13	22
5	X70	8	14	18

Note, in Incident 2 (X70 / X80 transition weld) the level of girth weld under-match would be much larger when compared to the X80 pipe.

Although girth weld under-matching and HAZ softening were not always the primary causes of the failures they were contributory factors.

Figure 2 is a macro of a girth weld hardness map for Incident 1, which exhibited the highest level of under-matching and HAZ softening. The highest level of under-matching was observed in the weld root region.

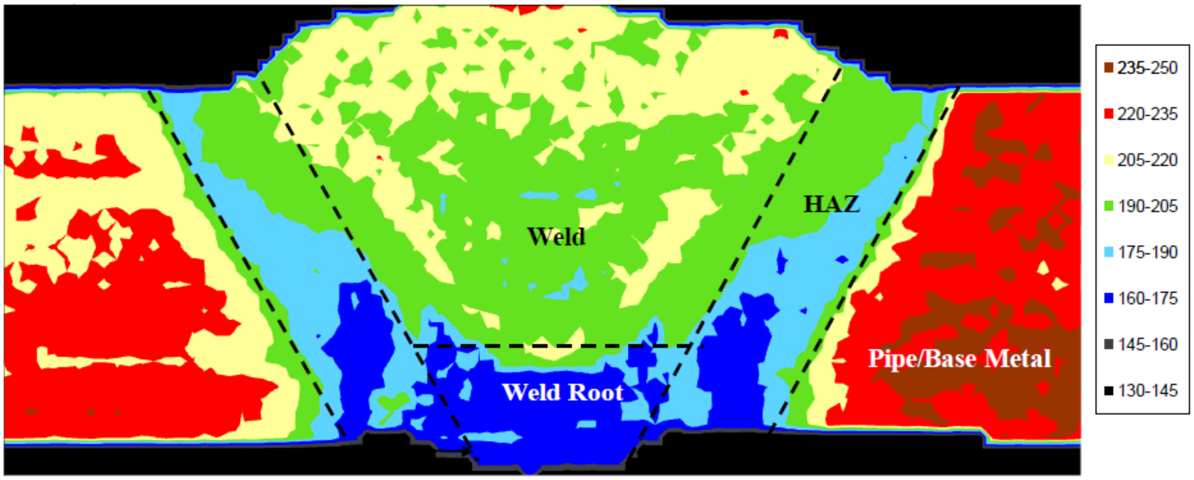


Figure 2. Hardness Map of a Girth Weld in Incident 1

Girth weld under-matching is a function of both the pipe longitudinal tensile properties and weld metal strength.

Girth weld over-matching can be facilitated by placing limits on pipe longitudinal tensile properties and adopting weld processes and procedures that produce higher strength weld metal.

HAZ softening is a function of several variables, including, but not limited to the following:

- Chemical composition of the pipe material;
- Rolling and thermal processing the steel experiences during steel production;
- Forming strains and work hardening that occurs during pipe manufacture;
- Girth welding parameters – in particular: heat input; and,
- HAZ cooling rate, which is a function of heat input, preheat and pipe wall thickness.

Based on the major findings from Phase 1 of the JIP, Phase 2 of the JIP set out to establish data that would enable the development of guidelines to mitigate low strain girth weld failures. The guidelines have three components:

1. Control pipe longitudinal tensile properties to facilitate girth weld over-matching;
2. Implement improved girth welding practices (processes and procedures) that produce over-matched girth welds. Further, include additional weld procedure qualification (WPQ) requirements to ensure over-matched girth welds; and,
3. Develop guardrails to minimize/control girth weld HAZ softening.

Sections 6 to 8 outline the three components of the mitigation strategy and provide recommended guidelines.

6 Pipe Longitudinal Tensile Properties

6.1 Comparison of SAWL vs. SAWH vs. ERW Pipe Manufacturing

Before comparing the tensile properties of longitudinally submerged arc welded pipe (SAWL), SAWH and High Frequency Electric Resistance Welded (HF-ERW) pipe it is important to recognize the differences in pipe manufacturing methods and the plastic strain cycles that steel plate/coil is subjected to during pipe manufacture.

Although pipe forming is common to all pipe forms (i.e., a plate or coil is formed into pipe), different pipe manufacturing methods introduce additional strain cycles described in Table 8.

Table 8. Comparison of Plastic Strain Cycles in Pipe Manufacture

Type of Pipe	Plastic Strain Cycles	Primary Direction Relative to Pipe
SAWL	Pipe forming	Transverse
	Cold expansion	Transverse
SAWH	Coiling and uncoiling of steel coils	Longitudinal
	Pipe forming	Mixed due to spiral
HF-ERW	Coiling and uncoiling of steel coils	Longitudinal
	Pipe forming	Transverse

The plastic strain cycles that occur during pipe manufacture can result in a change in the pipe tensile properties due to strain softening, strain hardening, and strain aging.

Strain softening, due to the Bauschinger effect, is illustrated in Figure 3. The Bauschinger effect is a phenomenon that occurs when materials are strained into the non-linear stress-strain area in one direction, followed by straining in the opposite direction. The effect of such cycling is that the reverse yield strength decreases.

Strain hardening (illustrated in Figure 4) is the effect seen when a material is strained in one direction, followed by unloading, before the material is strained in the same direction once more. The effect of such cycling is that the yield stress increases and the strain-hardening decreases.

Strain aging is a phenomenon whereby the material properties change (*age*) over time following plastic deformation (*straining*). The rate of change of material properties is dependent on the temperature, occurring more slowly at ambient temperature than at elevated temperatures. In steel, the change of material properties arising during aging is a result of the diffusion of interstitial carbon, nitrogen atoms, or both in the atomic lattice of the metal, to dislocations (i.e., discontinuities in the atomic structure). This leads to a *pinning* of the dislocations, making the steel more resistant to yielding.

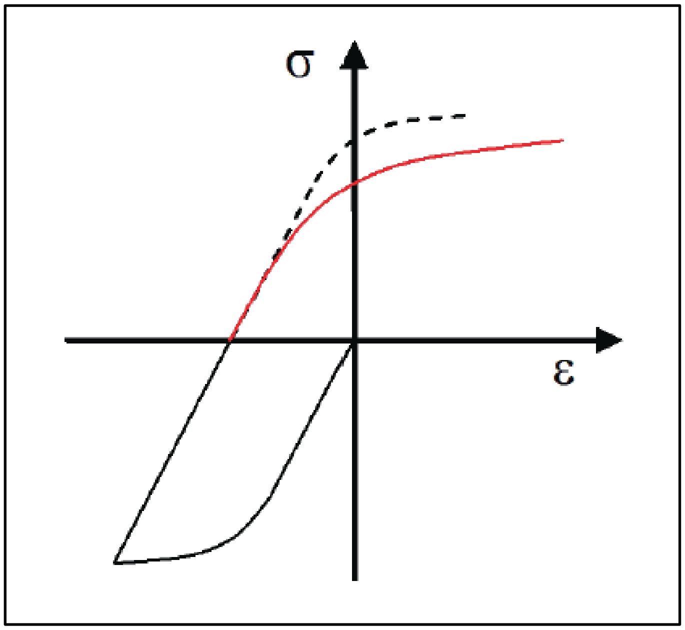


Figure 3. Bauschinger Effect

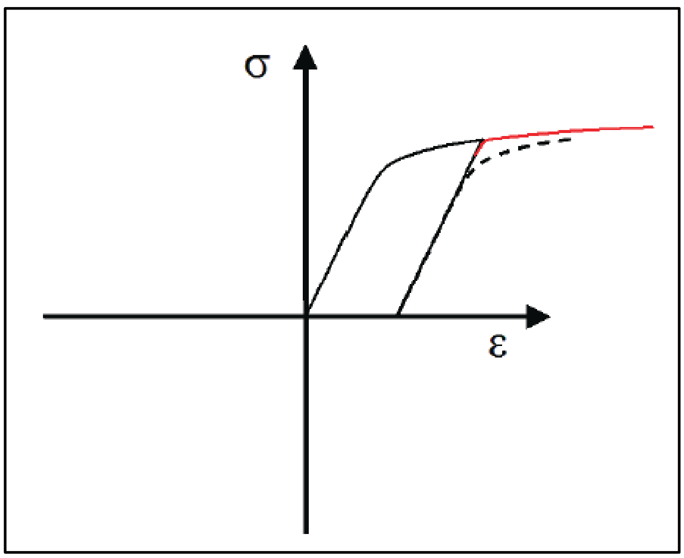


Figure 4. Strain Hardening

During pipe manufacture, the pipe material is subjected to plastic strain during pipe forming and cold expansion if applicable (e.g., SAWL pipe). The plastic strain introduced during pipe manufacture can lead to strain aging, which can occur naturally over extended periods of time or during the fusion-bonded epoxy (FBE) coating process (where pipe is heated to a temperature where aging occurs much more rapidly).

Strain aging is a complex function of several variables, including:

- Aging temperature and time;
- Steel composition/microstructure;
- Position through the pipe WT (i.e., ID, centerline or OD); and,
- Imposed strain cycles during pipe forming and expansion (if applicable).

The main effects of strain aging include [5-7]:

- An increase in the material yield and tensile strength;
- An increase in the material yield (yield strength) to tensile (tensile strength) ratio (Y/T) ratio;
- A reduction in uniform elongation; and,
- An increased potential to exhibit discontinuous yielding (Luders yielding) where the material exhibits a strain plateau at the material yield strength.

Given the different strain cycles imposed on steel plate/coil during pipe manufacture, and the primary strain directions relative to the final pipe orientation, some variation in the tensile properties of SAWL, SAWH, and HF-ERW pipe is expected.

6.2 Grade X70 Database

In Phase 2 of the JIP, the project developed a comprehensive database of Grade X70 pipe properties.

The major objectives of this task included:

1. Determine tensile property (YS, TS, Y/T) distributions (transverse and longitudinal) for Grade X70 SAWL, SAWH, and ERW pipe; and,
2. Compare SAWL, SAWH, and ERW tensile property distributions.

These data were collected from pipe mills and entered into the database by pipe category (i.e., SAWL, SAWH, and HF-ERW):

1. Parent pipe chemical composition;
2. Transverse and longitudinal tensile properties (YS, TS, % El, Y/T etc.); and,
3. Seam weld hardness data (weld, HAZ and parent pipe).

The data provided by the pipe mills were obtained from as-produced pipe (i.e., the tests were performed on pipe at the pipe mill prior to the pipe being FBE-coated).

The transverse tensile properties included in the database were obtained from tests on flattened strap specimens. Flattened strap tests are known to produce a) lower values of yield strength and b) increased variability in the measured yield strength as compared to non-flattened test specimens due to the Bauschinger effect. Although transverse tensile properties in pipe are generally measured using flattened strap specimens there are other tensile specimen designs that could be adopted to address this issue, e.g., round bar specimens or ring expansion tests, both of which are permitted by API 5L.

The data entered into the JIP Grade X70 database comprises the following:

1. Number of pipe mills: 8

   American, Berg, Borusan, Durabond, Evraz, Jindal, Stupp, and Welspun

2. Number of plate mill suppliers: 3

   AM-Burns Harbor, BAO, and POSCO

3. Number of coil producers: 4

   ArcelorMittal-NS, ArcelorMittal-Bremen, US-Steel, Evraz and TISCO.

4. Pipe fabrication records:
   - SAWL: 3,404;
   - SAWH: 15,400;
   - HF-ERW: 9,767; and,
   - Total number of samples: 28,571.

5. Pipe diameters:
   - 20-in. to 46-in.

6. Pipe WTs:
   - 0.3-in. to 1.8-in.

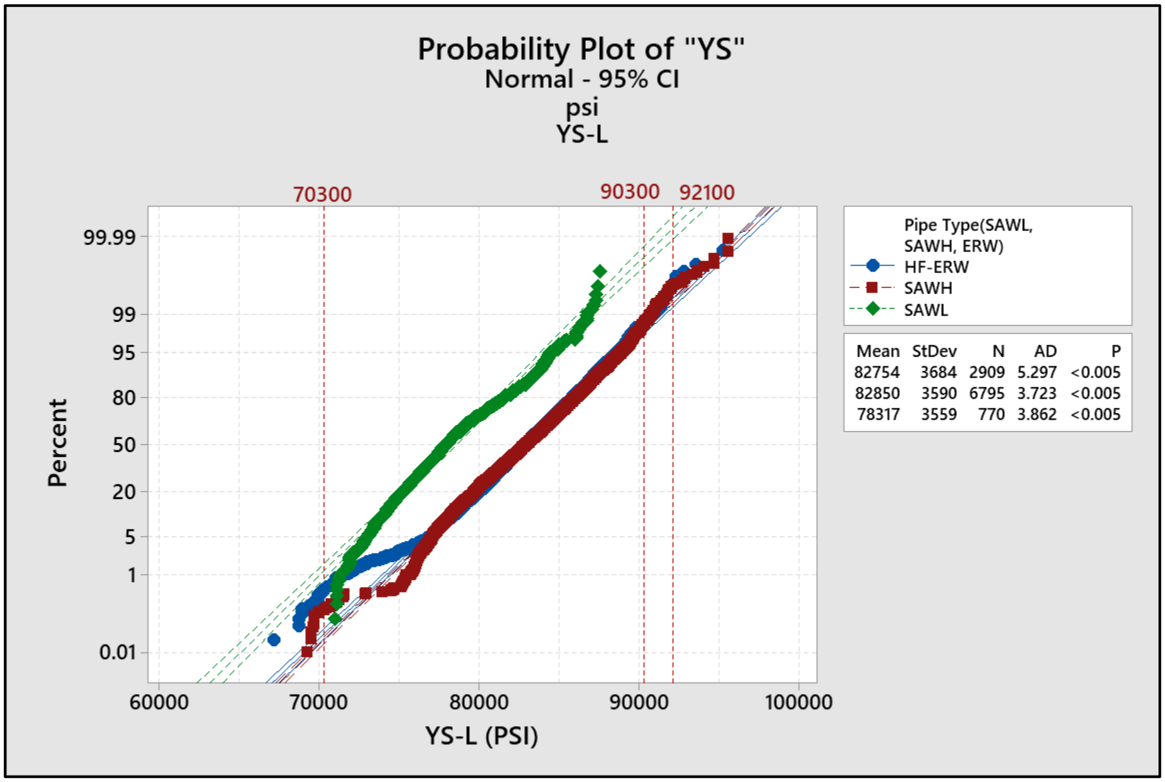
The Grade X70 Pipe Property Database confirmed that Grade X70 SAWH and HF-ERW pipe exhibit higher longitudinal tensile properties (YS-L, TS-L and Y/T-L) than SAWL pipe.

This is highlighted in Figure 5 which shows cumulative probability distribution plots of YS-L and TS-L for SAWL, SAWH and HF-ERW Pipe. Figure 6 presents the corresponding cumulative probability distribution plots of YS-T and TS-T.

Figure 5 and Figure 6 also include the specified minimum and maximum API 5L Product Specification Level 2 (PSL2) tensile property limits for YS-T and TS-T:

- YS-T:
  - SMYS = 70.3 ksi; and,
  - Specified Maximum Yield Strength = 92.1 ksi.
- TS-T:
  - SMTS = 82.7 ksi; and,
  - Specified Maximum Tensile Strength = 110.2 ksi.

Note, although API 5L contains YS-T and TS-T ranges for Grade X70 PSL2 pipe, it does not include YS-L or TS-L tensile property requirements for pipe with ODs > 8.625 in.



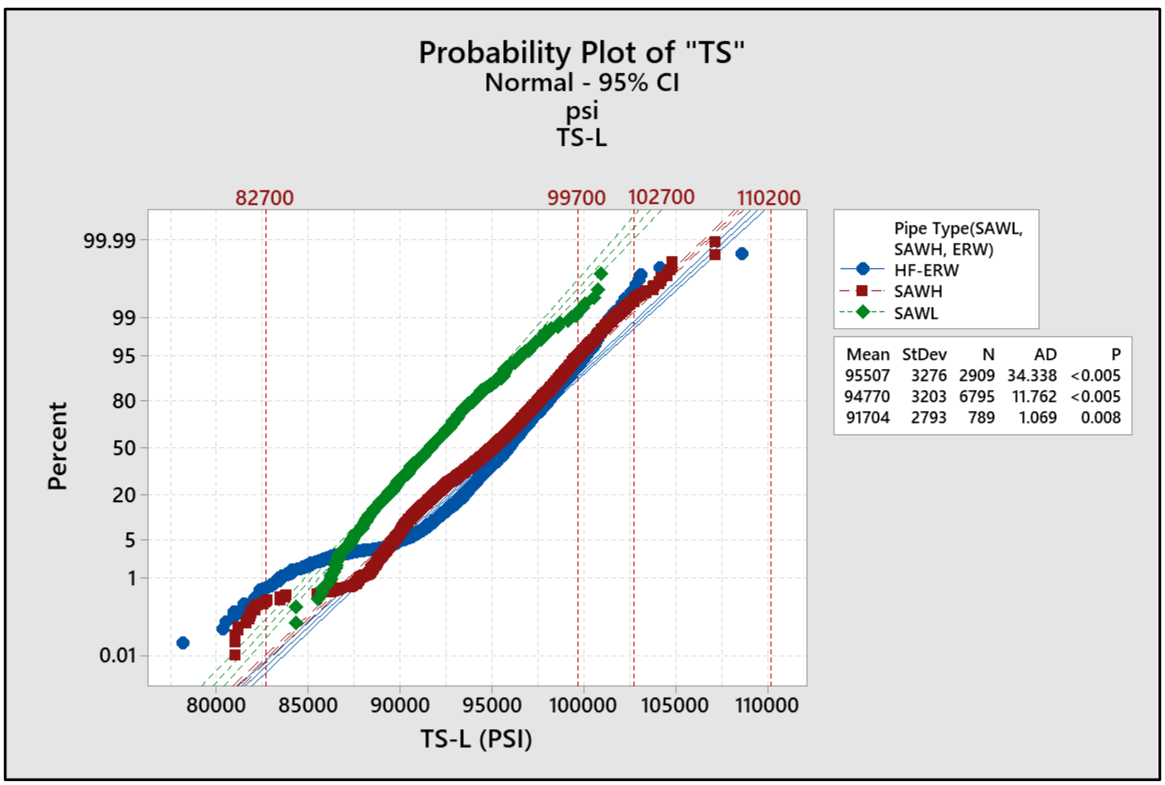
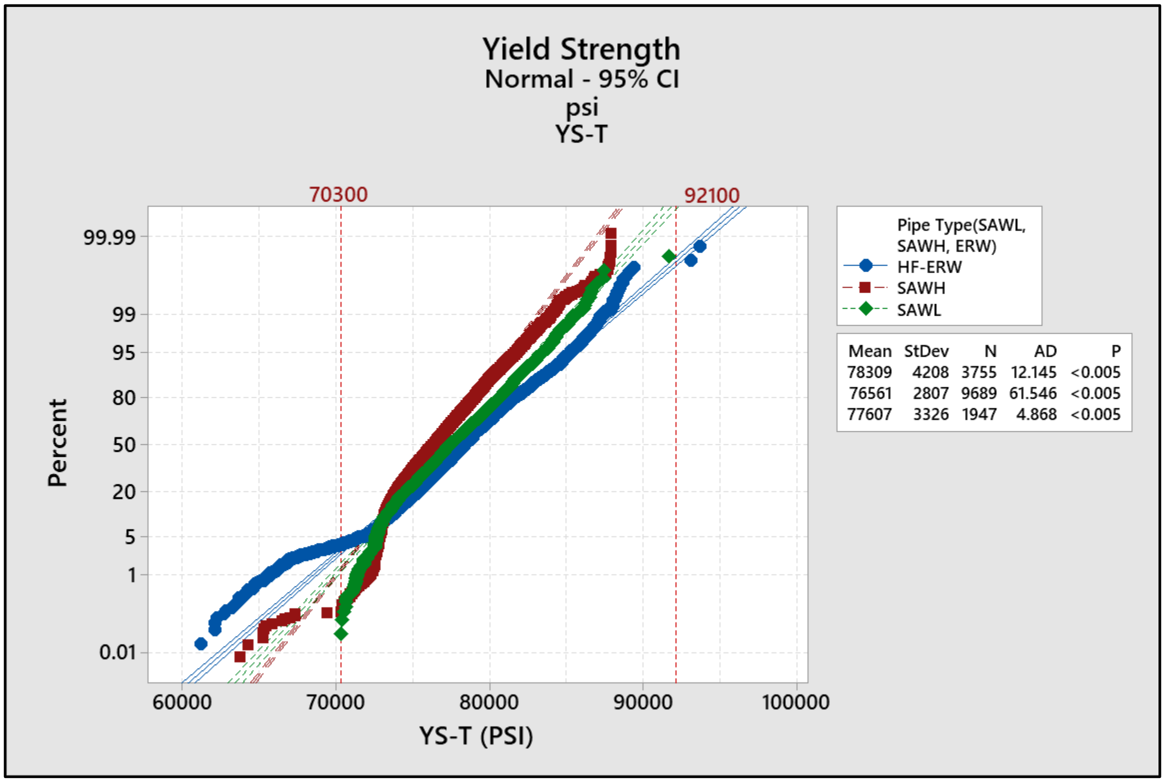


Figure 5. Cumulative Probability Distribution Plots for YS-L and TS-L



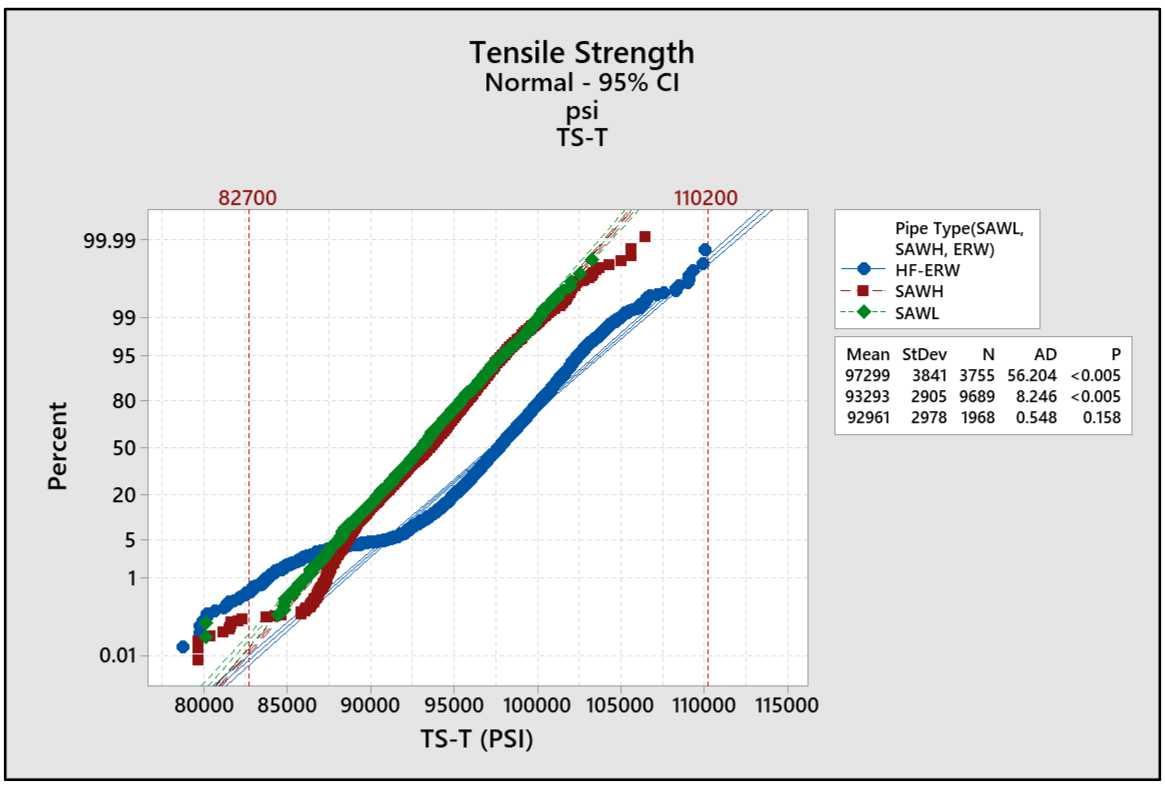


Figure 6. Cumulative Probability Distribution Plots for YS-T and TS-T

6.2.1 Longitudinal Tensile Properties

- SAWH and HF-ERW pipe exhibit higher average YS-L values than SAWL pipe (~ 4-5 ksi);
- Average YS-L values were 78.3 ksi (SAWL), 82.8 ksi (SAWH), and 82.9 ksi (HF-ERW);
- SAWH and HF-ERW pipe exhibit higher average TS-L values than SAWL pipe (~3-4 ksi);
- Average TS-L values were 91.7 ksi (SAWL), 94.8 ksi (SAWH), and 95.6 ksi (HF-ERW); and,
- The 90 and 95% upper bound YS-L and TS-L values (ksi) are presented in Table 9.

Table 9. 90 and 95% Upper Bound YS-L and TS-L Values (ksi)

Property	SAWL	SAWH	HF-ERW
Average YS-L	78.3	82.8	82.9
90% YS-L	84.2	88.8	88.8
95% YS-L	86.6	91.2	91.3
Average TS-L	91.7	94.8	95.5
90% TS-L	94.5	98.0	98.8
95% TS-L	97.3	101.2	102.1

6.2.2 Transverse Tensile Properties

- SAWH, HF-ERW, and SAWL pipe exhibit similar YS-T values (within 2-3 ksi);
- Average YS-T values were 77.6 ksi (SAWL), 76.6 ksi (SAWH), and 78.3 ksi (HF-ERW);
- SAWL and SAWH pipe exhibit similar TS-T values. HF-ERW pipe exhibited higher TS-T values (3-4 ksi); and,
- Average TS-T values were 93.0 ksi (SAWL), 93.3 ksi (SAWH), and 97.3 ksi (HF-ERW).

6.2.3 Transverse vs. Longitudinal Properties

- Average YS-L and YS-T values are very similar for SAWL pipe;
- Average YS-L values are approximately 4-5 ksi higher than YS-T for SAWH and HF-ERW pipe;
- Average TS-L and TS-T values are very similar for SAWL, SAWH, and HF-ERW; and,
- If it is assumed that the flattened tensile straps produce YS-T values that are ~ 5 ksi lower than non-flattened strap specimens, then it would be concluded that:
    - YS-L is lower than YS-T for SAWL pipes.
    - YS-L and YS-T are similar for SAWH and HF-ERW pipes.
    - TS-L and TS-T are similar for all three types.

6.3 As Produced vs. Aged Properties

As noted previously, the results presented in Figure 5 and Figure 6 were provided by pipe mills from as-produced pipe (i.e., the tests were performed on pipe at the pipe mill prior to FBE-coating).

After FBE-coating, the pipe properties will gain additional strength due to strain aging, which occurs from the thermal cycle associated with FBE-coating. Studies to investigate the effect of aging on Grade X70 pipe have confirmed that strain aging generally causes an increase in yield strength and tensile strength in longitudinal and transverse directions.

The following increases in YS-L and TS-L in Grade X70 pipe in the fully aged condition have been reported [5-7]:

- Increase in YS-L: 3 – 10 ksi; and,
- Increase in TS-L: 2 – 5 ksi.

Although the transverse tensile properties of pipe produced at a pipe mill are evaluated against the standard API 5L tensile property requirements and additional supplementary requirements specified by users, these tests are performed on as-produced pipe (i.e., bare pipe). Similarly, it is normal practice to ship bare pipe to a welding contractor for weld procedure development trials and WPQ.

However, after the pipeline is installed and in operation, it is the strain-aged tensile properties that will determine if the girth weld under-matches or over-matches the parent pipe. Although specifying or limiting longitudinal tensile properties in the *as-produced* condition will facilitate girth weld over-matching, as determined during WPQ, there is no guarantee that girth welds will continue to over-match the parent pipe when the pipeline is in operation.

6.4 Specification of Longitudinal Tensile Properties

Although it is reasonably common to specify longitudinal tensile property requirements for pipe used to construct offshore pipelines, it is not common practice to specify longitudinal tensile property requirements for cross-country pipelines.

For offshore pipeline projects, many line pipe specifications not only specify longitudinal tensile tests but also impose more restrictive limits on the maximum allowable longitudinal yield strength and tensile strength. This is due to the higher strains experienced by offshore pipelines during installation, especially pipelines installed by reeling. A common supplementary requirement for offshore pipelines is to limit the maximum pipe longitudinal tensile properties as follows:

- Maximum YS-L = SMYS + 17 ksi (120 MPa); and,
- Maximum TS-L = SMTS + 17 ksi (120 MPa).

The YS-L and TS-L tensile property distributions presented in Figure 5 and Figure 6 were analyzed to determine what percentage of pipe could meet maximum YS-L and TS-L caps of 17 and 20 ksi above specified minimum. Table 10 summarizes the percentage of pipes that meet maximum caps of 17 ksi and 20 ksi above specified minimum.

Table 10. Pipe Satisfying Maximum Caps on YS-L and TS-L

	YS-L (Max. Cap)		TS-L (Max. Cap)	
Pipe	SMYS + 17 ksi	SMYS + 20 ksi	SMTS + 17 ksi	SMTS + 20 ksi
SAWL	100%	100%	100%	100%
SAWH & HF-ERW	90%	98%	95%	>99%

Although the 17 ksi (120 MPa) or 20 ksi (140 MPa) caps are achievable for SAWL and seamless pipe, some pipe mills have expressed concern that these limits may be more difficult or impossible to achieve for SAWH and HF-ERW pipe. However, the 17 ksi (120 MPa) cap has been successively applied in several recent major United States (US) Grade X70 cross-country pipeline projects, where pipe was procured from three different SAWH pipe mills. This indicates that, with attention to detail, a 17 ksi (120 MPa) cap can be applied to SAWL, SAWH, and HF-ERW pipe.

6.5 Recommendations

To facilitate girth weld over-matching in Grade X70 pipelines, the Project Technical Team recommends that the following supplementary longitudinal tensile property requirements are specified for new pipe orders (SAWL, SAWH, and HF-ERW):

1. Longitudinal tensile tests should be performed at the same frequency as transverse tensile tests;
2. The longitudinal tensile tests should be performed on full thickness strap specimens;
3. The longitudinal tensile properties should fall within the following ranges:
    - YS-L = SMYS to SMYS + 17 ksi (120 MPa); and,
    - TS-L = SMTS to SMTS + 17 ksi (120 MPa).
4. The re-test provisions for longitudinal tensile tests should be the same as transverse tensile tests.

Although these requirements have been successfully applied in several recent major pipeline projects in which SAWH pipe was made at two different pipe mills, several steel producers and pipe mills have indicated that they will not be able to meet the 17 ksi cap requirement on YS-L and TS-L for SAWH and HF-ERW pipe. This in part is due to a) the current method of measuring transverse tensile properties in pipe using flattened strap specimens which tend to report lower values of yield strength due to the Bauschinger effect and b) concerns regarding under strength pipe. Both of these factors have caused Pipe Mills to over-specify tensile properties in plate or coil to provide a margin that allows for a reduction in the transverse yield strength in pipe as measured using flattened strap specimens. Although transverse tensile properties in pipe are generally measured using flattened strap specimens there are other tensile specimen designs that could be adopted that address this issue, e.g., round bar specimens or ring expansion tests, both of which are permitted by API 5L.

In addition, it is recommended that during manufacturing pre-production qualification testing (MPQT), longitudinal tensile tests are performed on pipe that has been aged at 250°C for one hour to determine the increase in YS-L and TS-L in the fully aged condition. The longitudinal tensile tests in the fully aged condition should be reported *For Information*. However, as more and more results are generated for longitudinal tensile properties in the fully aged condition, appropriate limits may be specified. The reason for specifying tensile properties in the fully aged condition is because they represent the properties that the pipe will exhibit during operation.

7 Girth Welding

7.1 General

The main goal of specifying supplementary girth weld requirements is to avoid gross weld under-matching and thereby ensure that girth welds are at least as strong or preferably over-match the longitudinal pipe properties. The supplementary requirements cover:

- Assurance of girth weld over-matching; and,
- General welding considerations.

The supplementary requirements have been developed using API 1104 as the base case code. API 1104 is the most widely used pipeline girth welding code in the world and has served the pipeline industry well for many years. There are extremely few pipeline girth weld failures in pipelines constructed in accordance with API 1104, thus confirming that the guidance included in API 1104 is acceptable for most pipelines and the loading conditions they experience during installation and operation. However, the recent failures that have been observed in Grade X70 pipeline girth welds that met the requirements of API 1104, which were constructed from pipe that met the requirements of API 5L, confirm that meeting code requirements is not sufficient to eliminate all failures.

7.2 API 1104 Weld Procedure Qualification Requirements

7.2.1 Project vs. Non-Project Pipe

Although Annex A of API 1104 requires girth weld qualification to be performed using project pipe, the main body of API 1104 permits girth weld procedures to be qualified on non-project pipe provided the girth weld procedure is restricted to the group of grades of pipe used to qualify the weld procedure.

API 1104 specifies these pipe material groups (Clause 5.4.2.2: 21st Edition):

- SMYS less than or equal to that of the material specified as API 5L Grade X42;
- SMYS greater than that of the material specified as API 5L Grade X42, but less than that of the material specified as API 5L Grade X65; and,
- For materials with an SMYS greater than or equal to that of the material specified as API 5L Grade X65, each grade shall receive a separate qualification test.

When welding materials of two separate material groups, the procedure for the higher strength group shall be used.

API 1104 contains the following precautionary note regarding qualification on non-project pipe material; however, it does not provide guidance or requirements on how *compatibility* should be evaluated (Clause 5.4.2.2: 21st Edition):

> *The groupings specified do not imply that base materials or filler metals of different analyses within a group may be indiscriminately substituted for a material that was used in the qualification test without consideration of the compatibility of the base materials and filler metals from the standpoint of metallurgical and mechanical properties and requirements for preheat and PWHT.*

Although API 1104 may accept qualification of girth weld procedures for Grade X70 pipe on non-project pipe, it is recommended that all girth weld procedures are qualified on project pipe. There are many different alloy designs for Grade X70 pipe. Different alloy designs may respond differently to welding, may have different susceptibilities to HAZ softening, and exhibit significant variability in HAZ hardness. The qualification of girth weld procedures on Project pipe is mandated in the Australian Pipeline Code AS2885 (8).

In addition to qualifying girth weld procedures on project pipe, girth weld procedures should (ideally) be qualified on project pipe that has the highest longitudinal tensile properties in the pipe order. If all the pipe is produced before WPQ starts, this can be achieved by reviewing the pipe material test reports (MTRs), which should contain longitudinal tensile test results, to select the heat with the highest tensile properties. It should be noted the TS-T and TS-L values are generally very closely related and the “strongest” pipe could reasonably be selected based on the TS-T values. Regardless, even though this can be achieved if the full pipe order is produced it can still present logistical difficulties.

In many cases, the pipe used for WPQ is early production or, in some cases, First Day Production, in which case it is not possible to ensure it has the highest tensile properties. In such cases, it is important to confirm that the weld procedures were not qualified on pipe with longitudinal tensile properties that were at the low end of the property distribution.

As noted earlier, the longitudinal tensile properties of pipe material will increase over time due to natural aging or aging associated with FBE-coating. Although girth weld procedures qualified on project pipe may ensure that the WPQ welds over-match the parent pipe, they do not guarantee that over-matching will be maintained after the pipe material has aged. One way of addressing the effect of aging is to qualify weld procedures on pipe material that has been subjected to a simulated FBE thermal cycle. This can be achieved by running the WPQ pipe joints through an FBE-coating machine but without applying the coating (i.e., the pipe is subjected to the FBE thermal cycle, but is not coated). Pipe mills with an FBE-coating facility can easily handle this step.

In summary, girth weld procedures should be qualified on project pipe and, ideally, on pipe with longitudinal tensile properties that are at the upper range of the pipe order. In addition, consideration should be given to performing WPQ on pipe that has been subjected to an FBE thermal cycle to account for aging.

7.2.2 Girth Weld Over-Matching

Although API 1104 requires that CWT tensile tests are performed during WPQ to characterize the strength of the girth weld, API 1104 does *not* require girth weld over-matching.

The requirements in the main body of API 1104 for both conventional CWT tests (weld cap and root not removed) and reduced section tensile (RST) specimens (weld cap and root machined-off) are as follows (Clause 5.6.2.3: 21st Edition):

a) The tensile strength of the weld, including the fusion zone of each specimen, shall be greater than or equal to the specified minimum tensile strength (SMTS) of the pipe material but need not be greater than or equal to the actual tensile strength of the material. If the specimen breaks outside the weld and fusion zone (i.e. in the parent metal) at a tensile strength not less than 95 % of that of the SMTS of the pipe material, the weld shall be accepted as meeting the requirements.

b) *If the specimen breaks in the weld or fusion zone and the observed strength is greater than or equal to the SMTS of the pipe material and meets the soundness requirements of 5.6.3.3, the weld shall be accepted as meeting the requirements.*

c) *If the specimen breaks in the weld and below the SMTS of the pipe material, the weld shall be set aside, and a new test weld shall be made.*

Note, the 20th Edition of API 1104 (which is currently incorporated by reference in the Federal Code of Regulations [CFR]) does not include the 95% SMTS limit.

If girth weld procedures (typically mechanized GMAW girth weld procedures) are qualified per API 1104 Annex A to permit the application of alternative engineering critical assessment (ECA) based girth weld flaw acceptance criteria, RST tests (weld reinforcement removed) are required. The requirements in Annex A are as follows (Clause A3.4.1.2: 21st Edition):

a) *If the specimen breaks at a strength equal to or greater than the SMTS of the pipe, the result is acceptable, and no further testing is required. Although tensile specimen failure in the weld is acceptable, provided the strength requirement is met, gross weld strength under-matching should be avoided.*

b) *If the specimen breaks in the weld or HAZ at a strength below the SMTS of the pipe material, the weld shall be rejected.*

c) *If a specimen breaks outside the weld or HAZ at a tensile strength less than 100 %, but not less than (lower than) 95 % of the SMTS of the pipe material, then two additional specimens may be tested. Both retest specimens shall meet the SMTS of the pipe material. If either retest specimen fails to meet the minimum tensile strength requirement, no retesting is permitted.*

d) *Any specimen that breaks outside the weld or HAZ at a tensile strength less than (lower than) 95 % of the SMTS of the pipe material shall be rejected and no further retesting is permitted.*

Note, the 20th Edition of API 1104 (which is currently incorporated by reference in the Federal Code of Regulations [CFR]) does not include the 95% SMTS limit.

It is evident from the above requirements that, although API 1104 (main body and Annex A) requires girth weld over-matching based on specified minimum tensile properties, API 1104 does *not* require absolute girth weld over-matching based on actual pipe properties.

In the limit, API 1104 will accept a girth weld in a Grade X70 pipe that has a CWT strength of 82.7 ksi. Even if a 17 ksi cap is applied to pipe longitudinal tensile properties, Grade X70 pipe could have a longitudinal yield strength as high as 87.3 ksi. In such extreme cases, the weld metal may reach its tensile strength before the pipe starts to yield (i.e., all the strain would focus into the girth weld).

Although girth weld over-matching based on specified minimum tensile properties is adequate for most girth welds, it can present problems in situations where unexpected local strains develop due to ground movement, subsidence, or the pipe not following the profile of the ditch. In such cases, there is the potential that high local strains may develop in under-matched girth welds, leading to girth weld failures – even in pipelines that use conventional stress-based design principles (e.g., nominal strain <0.50%).

Many other international codes and standards for pipeline welding, including CSA-Z662-19(9), BS 4515-1(10), ISO 13847(11), AS2885.2:2016(8), and ASME Section IX(12), have their roots in API 1104 and, for pipelines constructed using workmanship-based acceptance criteria, the tensile testing requirements in all of these international codes and standards simply mirror those in API 1104. Only AS2885.2 requires procedure qualification on project pipe and all allow tensile test specimens to break in the weld as long as they do so above the specified-minimum tensile strength of the pipe material (or 95% thereof).

Based on the above, it is important to have girth welds that over-match actual pipe properties as opposed to minimum specified properties. Unfortunately, it is impossible to guarantee weld metal over-matching by testing CWT specimens unless the pipe that is being tested has the highest longitudinal tensile properties in the pipe order. Even then, as noted previously, the tensile properties of the pipe in the installed condition will be higher than the properties of the same pipe during WPQ due to strain aging.

There are two CWT specimen geometries included in the main body of API 1104, 21st Edition:

- Conventional Cross-Weld (Weld Cap and Root not machined-off); and,
- Reduced Section Tensile (Weld Cap and Root can either be left in place or machined-off).

Real girth welds have weld caps and roots. The weld reinforcement in the weld cap and root provides additional strength to the girth weld. Although credit can be taken for weld reinforcement, performing CWT tests on RST specimens with the weld reinforcement removed provides increased confidence that girth weld over-matching will be achieved in production welds where potential variability in pipe and weld metal properties, and weld cap and root reinforcement, will occur.

For mechanized GMAW welds qualified to API 1104 Annex A, RST tests with the weld reinforcement removed are required. This requirement is justified because Annex A permits the application of alternative ECA flaw acceptance criteria, which in most cases, extend well beyond standard workmanship criteria. In such cases, girth weld over-matching is critical given the more relaxed flaw acceptance criteria even though it is not required by API 1104 Annex A.

For SMAW and SMAW/FCAW girth weld procedures, it is recommended that CWT tests are performed on specimens with the weld reinforcement in place because:

- Leaving the weld reinforcement in place is more representative of actual girth welds; and,
- SMAW and SMAW/FCAW girth welds are normally inspected to standard workmanship flaw acceptance criteria as opposed to ECA criteria for mechanized GMAW girth welds qualified to API 1104 Annex A which are generally much more relaxed.

The current version of API 1104 includes these limits on weld reinforcement:

- The internal diameter (ID) weld reinforcement shall not be raised above the parent material by more than 1/16 in. (2 mm); and,
- The outside diameter (OD) weld reinforcement shall not be raised above the parent material by more than 1/8 in. (3 mm).

An alternative method to guarantee girth weld over-matching is to perform all weld metal tensile tests (AWT). However, AWT tests are not without their challenges in terms of obtaining consistent and representative results, including the effect of using lower strength consumables (e.g., E6010) in the weld root. AWTs are also difficult to perform on small diameter pipe where the tensile specimen will only sample weld metal in the root region because of the curvature of the pipe. Canmet(13) has developed recommended guidelines for performing AWTs on girth welds. These guidelines should be followed if AWTs are specified. These guidelines are also included in AWS B4.0 (14).

In summary, although CWT tests are used to characterize the strength of girth welds, they do not necessarily guarantee girth weld over-matching – even if the specimens fail in the base pipe material.

Although API 1104 includes the following requirement …

> *The tensile strength of the weld, including the fusion zone of each specimen, shall be greater than or equal to the specified minimum tensile strength (SMTS) of the pipe material but need not be greater than or equal to the actual tensile strength of the material.*

… this can result in under-matched girth welds. Although this may be acceptable to code, this acceptance requirement does not represent best practice. Nor does it ensure adequate girth weld performance. Instead, the requirement for CWT tests should be that failure should occur in the base pipe, i.e., failure in the girth weld or HAZ is not acceptable.

It is important to note that although girth weld overmatching will prevent strain accumulation in the girth weld (not necessarily the HAZ) excessive girth weld over-matching can lead to other issues. In general increases in weld metal strength come at the expense of toughness. As a result, using a girth weld procedure that significantly over-matches the parent pipe (e.g., >20% over-match) can lead to girth welds with poor toughness. As a result, using a weld procedure that produces a high level of over-match can solve the problem of strain accumulation in the girth weld but can create girth welds with poor toughness and the increased risk of brittle fracture, i.e., it solves one problem but in the process creates a different problem. It is important that girth weld overmatching is achieved by firstly controlling the pipe longitudinal tensile and then selecting appropriate welding consumable(s) that provides girth weld over-matching but avoid the need to use extremely high strength welding consumables.

7.3 General Welding Considerations

7.3.1 General

The recent Grade X70 girth weld failures were all in SMAW or SMAW/FCAW girth welds (i.e., no low strain tensile failures have been reported in GMAW girth welds). This is an expected outcome because the mechanized GMAW girth welds have these features:

- Narrow welds in comparison to SMAW/FCAW girth welds;
- Weld preparation with near-vertical sidewalls;
- Low heat input, which leads to a narrow HAZ;
- Reduced HAZ softening due to low heat input; and,
- Higher achievable weld metal strength without the risk of weld metal hydrogen cracking.

By comparison, SMAW or SMAW/FCAW girth welds have these features:

- Wider welds than mechanized GMAW welds;
- Weld preparations, which have fusion lines that are much closer to the preferred 45° slip planes that facilitate yielding and plastic deformation;
- SMAW or SMAW/FCAW girth welds are generally made using higher heat input than mechanized GMAW welds, resulting in wider HAZs and increased potential for HAZ softening; and,

- Lower achievable weld metal strength for cellulosic-coated SMAW electrodes due to the risk of weld metal hydrogen cracking.
- Greater scatter in material properties (vs. mechanized GMAW) due to the welding manual process, and especially more so for manual FCAW.

It may be too early to state categorically that low strain girth weld failures are limited to SMAW or FCAW girth welds. However, it is clear that, SMAW and FCAW girth welds are more susceptible to low strain tensile failures than GMAW welds, particularly in thin wall pipes (e.g., <0.375 in.) where:

- The use of a lower strength weld consumable for the root pass results in a large proportion of the overall weld thickness comprised of lower strength weld metal; and,
- The HAZ width is a significant proportion of the pipe wall thickness.

Given the above, SMAW and SMAW/FCAW girth welds in thin wall Grade X70 pipe require special consideration.

Submerged arc weld (SAW) double-joint girth welds also require consideration. Many pipeline projects use double-joints to reduce pipeline construction costs. Double-joint girth welds are normally manufactured using SAW to ensure high productivity and high-quality welds at a competitive cost. SAW generally uses a much higher heat input welding process than SMAW/FCAW. Hence, it tends to produce girth welds with wider and softer HAZs – raising potential concerns with HAZ softening, particularly on steels that are susceptible to HAZ softening.

Although SAW girth welds may contain wider/softer HAZs than SAW/FCAW girth welds, SAW girth welds are less susceptible to failures from HAZ softening for these reasons:

1. The selection of SAW welding wires and fluxes generally produce high strength (over-matched), high toughness girth welds. As discussed in Section 7, girth weld over-matching can protect soft HAZs and reduces the potential for failures due to HAZ softening; and,
2. SAW double-joint girth welds are normally manufactured using a double-V procedure (i.e., they are welded from the ID and OD). This double-V weld geometry is less susceptible to HAZ failures because it does not favor failures along a 45° slip plane.

7.3.2 SMAW Girth Weld Test Program

For SMAW girth welds in Grade X70 pipe, it is common practice to deposit the root pass with E6010 consumables (cellulosic) to ensure a high-quality weld root, good profile, and no undercut. The use of E6010 for the root pass allows contraction strains to be accommodated in the low-strength weld metal, as opposed to what has traditionally been the more crack-susceptible HAZ. Indeed, over the last 20 to 30 years, electrode manufacturers developed E6010 electrodes with root pass welding specifically in mind. These electrodes have good operability in the field and, consequently, are favored by pipeline welders for root pass welding.

For Grade X70 pipe, the hot pass, and fill-and-cap passes are typically welded using E8010 consumables. If the hot pass is also deposited using an E6010 consumable, then the weld root and hot pass will significantly under-match the parent pipe. Furthermore, in the case of thin wall pipe, the combined thickness of the root and hot pass may exceed 50% of the pipe WT.

It is important to recognize that the first two digits in an electrode designation (e.g., 60 in E6010) represent the minimum required tensile strength of the deposited weld metal in ksi. Consequently, although an E8010 consumable may appear appropriate to weld Grade X70 pipe, it is important to recognize that – even if a 17 ksi cap is specified for pipe longitudinal tensile properties – Grade X70 pipe can have a longitudinal yield strength of up to 87.3 ksi and a longitudinal tensile strength up to 99.7 ksi (i.e., the use of an 80 ksi consumable does not guarantee over-match). Indeed, this can result in a grossly under-matched girth weld in which the weld metal has a tensile strength lower than the pipe yield strength.

One of the tasks in Phase 2 of the JIP included testing Grade X70 girth welds donated by JIP members to characterize the pipe and girth weld properties. A total of 15 girth weld samples were tested (14 SMAW girth welds and 1 SAW double-joint girth weld). Many of these girth weld samples were welds removed from pipelines that were constructed more than 20 years ago. The test program included:

- AWTs; and,
- CWT tests.

A summary of the chemical compositions of the pipe either side of the girth weld in the girth weld samples (Pipe A and Pipe B are presented in Table 11).

Some of the girth weld samples exhibited significant differences in parent pipe chemical composition either side of the girth weld (e.g., samples 101229, 102706, 102658 and 104629). This will result in the formation of two different HAZ microstructures on either side of the girth weld which may lead to different HAZ properties and susceptibility to HAZ softening and result in a concentration in strain on one side of the girth weld.

Table 11. Chemical Composition of Pipe Materials in Girth Weld Samples

Sample	Plate ID	C	Mn	P	S	Nb	V	Ti	N	Al	Si	Cr	Mo	Cu	Ni	B	Ca	Pcm
101171	Pipe A	0.067	1.70	0.007	0.004	0.040	<0.01	<0.01	<0.005	0.040	0.24	0.160	<0.01	<0.01	<0.01	<0.0005	<0.005	0.168
	Pipe B	0.064	1.70	0.007	0.004	0.040	<0.01	<0.01	<0.005	0.040	0.24	0.150	<0.01	<0.01	<0.01	<0.0005	<0.005	0.165
101223	Pipe A	0.084	1.58	0.009	0.004	0.060	0.040	0.020	0.006	0.040	0.27	0.200	<0.01	<0.02	<0.01	<0.0005	<0.005	0.182
	Pipe B	0.082	1.64	0.010	0.004	0.060	0.040	0.020	<0.005	0.050	0.29	0.210	<0.01	<0.02	<0.01	<0.0005	<0.005	0.184
101227	Pipe A	0.087	1.61	0.009	0.004	0.060	0.040	0.020	<0.005	0.040	0.26	0.210	<0.01	0.030	<0.01	<0.0005	<0.005	0.187
	Pipe B	0.084	1.61	0.008	0.004	0.060	0.040	0.020	<0.005	0.040	0.25	0.200	<0.01	0.040	<0.01	<0.0005	<0.005	0.183
101228	Pipe A	0.063	1.57	0.009	0.006	0.060	0.020	0.010	<0.005	0.040	0.28	0.030	0.130	0.170	0.120	<0.0005	<0.005	0.152
	Pipe B	0.064	1.55	0.010	0.007	0.050	0.020	0.010	<0.005	0.040	0.28	0.020	0.130	0.170	0.120	<0.0005	<0.005	0.152
101229	Pipe A	0.110	1.62	0.012	0.004	0.070	<0.01	0.020	<0.005	0.040	0.36	0.040	0.010	0.020	0.020	<0.0005	<0.005	0.205
	Pipe B	0.077	1.67	0.010	0.005	0.060	<0.01	0.020	<0.005	0.030	0.25	0.270	0.060	0.230	0.140	<0.0005	<0.005	0.182
101231	Pipe A	0.094	1.62	0.010	0.004	0.060	0.040	0.020	<0.005	0.040	0.26	0.190	0.070	0.020	<0.01	<0.0005	<0.005	0.193
	Pipe B	0.084	1.62	0.010	0.004	0.070	0.040	0.020	<0.005	0.040	0.27	0.190	0.080	0.020	0.020	<0.0005	<0.005	0.184
101232	Pipe A	0.097	1.57	0.014	0.004	0.070	<0.01	0.010	<0.005	0.030	0.21	0.020	<0.01	0.010	<0.01	<0.0005	<0.005	0.184
	Pipe B	0.096	1.58	0.014	0.004	0.060	<0.01	0.010	<0.005	0.030	0.22	0.020	<0.01	0.010	<0.01	<0.0005	<0.005	0.183
101276	Pipe A	0.056	1.68	0.010	0.007	0.090	<0.01	0.010	<0.005	0.040	0.27	0.270	0.060	0.370	0.100	<0.0005	<0.005	0.163
	Pipe B	0.057	1.68	0.009	0.006	0.090	<0.01	0.010	<0.005	0.030	0.27	0.270	0.060	0.370	0.100	<0.0005	<0.005	0.164
101279	Pipe A	0.055	1.67	0.010	0.007	0.080	<0.01	0.010	<0.005	0.030	0.28	0.270	0.060	0.370	0.100	<0.0005	<0.005	0.161
	Pipe B	0.057	1.68	0.011	0.008	0.090	<0.01	0.020	<0.005	0.040	0.28	0.270	0.060	0.370	0.100	<0.0005	<0.005	0.164
102658	Pipe A	0.083	1.37	0.007	0.006	0.069	0.050	0.010	0.004	0.030	0.29	0.250	0.009	0.030	0.008	<0.0002	0.0020	0.174
	Pipe B	0.094	1.38	0.006	0.008	0.062	0.060	0.010	0.004	0.030	0.34	0.260	0.007	0.020	0.006	<0.0002	0.0020	0.187
102659	Pipe A	0.086	1.47	0.007	0.008	0.069	0.060	0.010	0.004	0.030	0.34	0.270	0.006	0.030	0.009	<0.0002	<0.001	0.184
	Pipe B	0.088	1.39	0.006	0.006	0.062	0.050	0.010	0.004	0.030	0.31	0.250	0.009	0.030	0.008	<0.0002	0.0040	0.180
102706	Pipe A	0.032	1.55	0.011	0.005	0.060	0.030	0.010	0.005	0.030	0.22	0.030	0.130	0.170	0.120	<0.0002	0.002	0.118
	Pipe B	0.049	1.41	0.011	0.005	0.050	0.030	0.020	0.004	0.030	0.25	0.030	0.120	0.180	0.110	<0.0002	0.003	0.129
102707	Pipe A	0.054	0.38	0.010	0.003	0.080	0.004	0.010	0.004	0.050	0.16	0.420	0.010	0.250	0.120	<0.0002	0.002	0.110
	Pipe B	0.053	0.37	0.010	0.003	0.070	0.004	0.010	0.004	0.050	0.15	0.420	0.009	0.250	0.120	<0.0002	0.002	0.109
104629	Pipe A	0.070	1.75	0.009	0.006	0.090	<0.01	0.010	0.004	0.040	0.28	0.030	0.005	0.010	0.040	0.0009	0.002	0.174
	Pipe B	0.081	1.73	0.009	0.006	0.100	<0.01	0.020	0.004	0.040	0.28	0.020	0.006	0.020	0.040	0.0011	0.003	0.185
107263	Pipe A	0.050	1.66	0.010	0.003	0.090	0.004	0.015	<0.005	0.032	0.26	0.260	0.060	0.390	0.110	0.0003	0.0021	0.182
	Pipe B	0.050	1.66	0.010	0.003	0.090	0.004	0.015	<0.005	0.032	0.26	0.260	0.060	0.390	0.110	0.0003	0.0021	0.182

The CWT specimens were instrumented so that strain could be measured in Pipe A, Pipe B, and across the girth weld with a range of gauge lengths that permitted weld strain, and weld and HAZ strain to be determined.

The following CWT tests were performed on each girth weld sample:

- Two CWT tests with weld cap and weld root in place; and,
- Two CWT tests with weld cap and weld root machined-off.

All CWT tests were performed on reduced section specimens. The CWT tests were performed at room temperature. Table 12 and Table 13 summarize CWT test results.

Table 12 summarizes the following tensile properties:

- Average YS-L: Pipe A (four tests);
- Average YS-L: Pipe B (four tests);
- Average TS-L: Pipe A (four tests);
- Average TS-L: Pipe B (four tests);
- AWT results (YS and TS); and,
- Calculated Girth Weld Over-match (YS and TS).

The girth weld under/over -match was calculated based on both yield strength and tensile strength. Positive numbers indicate under-matching. It is clear from Table 12 that all 15 girth weld procedures tested under-matched the pipe based on yield strength. Two of the fifteen girth welds over-matched based on tensile strength. The remaining girth welds under-matched based on tensile strength.

The cells highlighted in red in Table 13 are results where the failure location was in the weld or weld/HAZ region. Of the 15 girth welds tested, 4 exhibited failures in the weld/HAZ on samples where the weld reinforcement was left in place. By contrast, 11 of the 15 girth welds exhibited failures in the weld/HAZ when the weld reinforcement was removed. This indicates that, in many cases, the weld reinforcement was enough to move the failure location from the weld/HAZ to parent pipe.

Table 12. Parent Pipe and AWT Tensile Results from CWT Tests

Sample	Diameter (inch)	Wall Thickness (inch)	Pipe	Parent Pipe		AWT		Undermatch (%)	
				Avg YS-L (ksi)	Avg TS-L (ksi)	YS (ksi)	TS (ksi)	YS	TS
101171	36	0.540	A	82.5	89.0	71.0	85.5	12.3%	2.6%
			B	81.0	87.8				
101223	36	0.438	A	84.5	93.0	59.0	79.5	30.2%	13.1%
			B	85.5	91.5				
101227	36	0.375	A	84.7	93.5	69.5	92.5	17.9%	1.1%
			B	87.0	93.5				
101228	42	0.510	A	85.3	93.3	69.5	82.0	18.5%	11.9%
			B	87.5	93.1				
101229	36	0.515	A	81.0	91.8	72.5	90.5	10.5%	1.4%
			B	81.5	92.9				
101231	30	0.625	A	87.3	96.7	73.5	87.0	15.8%	10.0%
			B	89.8	97.1				
101232	36	0.515	A	80.6	92.0	65.5	85.5	18.7%	6.6%
			B	83.8	91.5				
101276	30	0.476	A	85.8	> 95	65.0	81.5	24.2%	-
			B	86.0	> 95				
101279	30	0.476	A	85.6	> 95	70.0	87.0	18.2%	-
			B	85.6	> 95				
102658	30	0.375	A	79.5	91.0	70.0	84.5	11.9%	6.4%
			B	79.5	90.3				
102659	30	0.375	A	75.8	88.0	70.0	88.5	2.8%	-7.3%
			B	72.0	82.5				
102706	24	0.375	A	87.5	93.8	80.5	93.0	8.0%	0.9%
			B	88.7	94.3				
102707	20	0.750	A	76.8	85.2	74.0	88.5	3.6%	-4.7%
			B	78.3	84.5				
104629	48	0.688	A	90.0	> 90	68.5	82.5	23.9%	-
			B	90.0	> 90				
107263	36	0.476	A	85.5	94.3	71.5	87.0	16.4%	7.7%
			B	87.0	96.0				

Table 13. Cross-Weld Tensile Test Results (Failure Stress)

Sample	Diameter (inch)	Wall Thickness (inch)	Weld Cap & Root in Place			Weld Cap & Root Removed		
			Test Specimen	Failure Stress (ksi)	Failure Location	Test Specimen	Failure Stress (ksi)	Failure Location
101171	36	0.540	1	90.4	Pipe A	1	86.9	Pipe A
			2	89.8	Pipe A	2	87.9	Pipe A
101223	36	0.438	1	90.6	HAZ - Pipe B	1	90.2	Weld
			2	89.9	HAZ - Pipe B	2	85.9	Weld
101227	36	0.375	1	90.6	Pipe B	1	91.1	Weld
			2	90.0	Pipe B	2	89.3	Weld / HAZ - Pipe B
101228	42	0.510	1	93.3	Pipe A	1	90.5	Weld
			2	93.5	Pipe B	2	89.6	Weld
101229	36	0.515	1	92.5	Pipe B	1	91.7	Weld
			2	92.5	Pipe B	2	89.9	Weld
101231	30	0.625	1	96.7	Pipe A	1	91.6	Weld
			2	96.3	Pipe A	2	90.2	Weld
101232	36	0.515	1	92.0	Pipe A	1	88.4	Weld
			2	93.1	Pipe B	2	90.8	Pipe A
101276	30	0.476	1	95.2	Weld / HAZ - Pipe B	1	89.0	Weld
			2	93.0	Weld / HAZ - Pipe B	2	90.2	Weld
101279	30	0.476	1	94.0	Weld / HAZ - Pipe A	1	89.8	Weld
			2	92.6	Weld	2	89.8	Weld
102658	30	0.375	1	82.0	Pipe A	1	81.3	Pipe A
			2	82.4	Pipe A	2	80.9	Pipe A
102659	30	0.375	1	82.6	Pipe B	1	82.0	Pipe B
			2	82.6	Pipe B	2	82.0	Pipe B
102706	24	0.375	1	94.9	Pipe A	1	89.1	HAZ - Pipe A
			2	94.4	Pipe A	2	88.1	HAZ - Pipe B
102707	20	0.750	1	85.9	Pipe B	1	84.8	Pipe B
			2	86.0	Pipe B	2	82.9	Pipe B
104629	48	0.688	1	89.9	Weld / HAZ - Pipe B	1	83.0	HAZ - Pipe B
			2	86.9	HAZ - Pipe A	2	85.3	HAZ - Pipe A
107263	36	0.476	1	97.0	Pipe B	1	91.5	Weld / HAZ - Pipe A
			2	95.8	Pipe B	2	92.6	Weld

Table 14 presents the same results presented in Table 13 in terms of the average pipe strain at maximum load (i.e., the average of the strain in Pipe A and Pipe B). The red highlighted cells are results where the failure location was in the weld or weld/HAZ region. The blue highlighted cells are tests where failure occurred at average pipe strains less than 1.0%.

Table 14. Cross-Weld Tensile Test Results (Failure Strain)

Sample	Diameter (inch)	Wall Thickness (inch)	Weld Cap & Root in Place			Weld Cap & Root Removed		
			Test Specimen	Avg Pipe Strain (%)	Failure Location	Test Specimen	Avg Pipe Strain (%)	Failure Location
101171	36	0.540	1	> 5	Pipe A	1	2.90	Pipe A
			2	> 5	Pipe A	2	2.50	Pipe A
101223	36	0.438	1	3.70	HAZ - Pipe B	1	0.32	Weld
			2	3.40	HAZ - Pipe B	2	0.39	Weld
101227	36	0.375	1	> 5	Pipe B	1	3.65	Weld
			2	> 5	Pipe B	2	3.60	Weld / HAZ - Pipe B
101228	42	0.510	1	> 5	Pipe A	1	3.30	Weld
			2	> 5	Pipe B	2	1.30	Weld
101229	36	0.515	1	> 5	Pipe B	1	4.50	Weld
			2	> 5	Pipe B	2	4.80	Weld
101231	30	0.625	1	> 5	Pipe A	1	2.85	Weld
			2	> 5	Pipe A	2	1.62	Weld
101232	36	0.515	1	> 5	Pipe A	1	> 5	Weld
			2	> 5	Pipe B	2	> 5	Pipe A
101276	30	0.476	1	> 5	Weld / HAZ - Pipe B	1	0.66	Weld
			2	5.00	Weld / HAZ - Pipe B	2	3.00	Weld
101279	30	0.476	1	4.70	Weld / HAZ - Pipe A	1	2.10	Weld
			2	4.70	Weld	2	0.36	Weld
102658	30	0.375	1	> 5	Pipe A	1	> 5	Pipe A
			2	> 5	Pipe A	2	> 5	Pipe A
102659	30	0.375	1	> 5	Pipe B	1	4.80	Pipe B
			2	> 5	Pipe B	2	> 5	Pipe B
102706	24	0.375	1	> 5	Pipe A	1	0.56	HAZ - Pipe A
			2	> 5	Pipe A	2	0.54	HAZ - Pipe B
102707	20	0.750	1	> 5	Pipe B	1	4.60	Pipe B
			2	> 5	Pipe B	2	> 5	Pipe B
104629	48	0.688	1	1.04	Weld / HAZ - Pipe B	1	0.29	HAZ - Pipe B
			2	0.36	HAZ - Pipe A	2	0.33	HAZ - Pipe A
107263	36	0.476	1	> 5	Pipe B	1	4.10	Weld / HAZ - Pipe A
			2	> 5	Pipe B	2	4.10	Weld

Sections 7.3.2.1 and 7.3.2.2 summarize main results and conclusions from the AWT and CWT, respectively.

7.3.2.1 AWT Results

1. Table 15 summarizes the average, minimum, and maximum AWT tensile properties for the E6010/8010 SMAW girth welds;

Table 15. AWT Test Results

Description	Yield Strength (ksi)	Tensile Strength (ksi)
Average	69.3	85.9
Minimum	59.0	79.5
Maximum	74.0	92.5

2. The AWT tensile properties for the SAW double-joint girth weld were:
    - YS = 80.5 ksi; and,
    - TS = 93.0 ksi.
3. The results of the AWTs confirm that traditional E6010/E8010 SMAW girth weld procedures can result in under-matched girth welds. The girth weld samples that were tested had average under-match levels of 17% based on YS and 11% based on TS; and,
4. The AWT results were compared against the Grade X70 longitudinal tensile property distributions from the X70 Database to determine average levels of under/over -match. The average AWT TS was 86 ksi. This corresponds to the 80th percentile (80%) of the SAWH and HF-ERW YS-L tensile property distribution (i.e., without the added strength benefit of weld reinforcement up to 20% of E6010/E8010 SMW girth welds may fail in the weld – and exceed the weld TS) before the pipe starts to yield.

7.3.2.2 CWT Results

1. Table 16 summarizes the average, minimum, and maximum CWT tensile strengths for the E6010/E8010 SMAW girth welds;

Table 16. CWT Results

Description	Tensile Strength (ksi)	
	Weld Cap/Root in Place	Weld Cap/Root Removed
Average	90.9	87.9
Minimum	82.0	80.9
Maximum	97.0	92.6

2. Four (4) of fifteen (15) girth welds tested exhibited CWT failures in the weld/HAZ on samples where the weld reinforcement was left in place;

3. Eleven (11) of fifteen (15) girth welds tested exhibited CWT failures in the weld/HAZ on samples where the weld reinforcement was removed. This indicates that, in many cases, the weld reinforcement was enough to move the failure location from the weld/HAZ to parent pipe;
4. In general, the CWTs exhibited initial yielding in the HAZ region with the strain concentration in the HAZ decreasing with increasing applied strain due to work hardening;
5. Five (5) of fifteen (15) girth welds tested failed at an average pipe strain of less than 1.0% when the weld cap and root were removed; and,
6. One (1) of fifteen (15) girth welds failed at an average pipe strain of less than 1.0% when the weld cap and root were left in place.
7. All the girth weld samples that failed at average pipe strains less than 1.0% were under-matched. Apart from the SAW Double Joint girth weld sample, which had a Carbon < 0.04% and a Pcm of 0.14, low strain failures occurred in girth weld samples with Carbon and Pcm levels as high as 0.08% and 0.185 respectively. This confirms that girth weld matching or over-matching is the most important factor in avoiding low strain girth weld failures, i.e., girth weld strength is the first line of defense in mitigating low strain girth weld failures.

7.3.3 SMAW Welding Consumables

The girth weld test results confirm that E6010/8010 SMAW girth welds do not consistently over-match Grade X70 pipe and may lead to low strain girth weld failures. This highlights the need to adopt higher-strength welding consumables.

Although girth weld over-matching would be more assured using a 90 ksi welding consumable, the use of a cellulosic 90 ksi consumable (E9010) introduces the risk of weld metal hydrogen cracking – particularly in WTs >0.250 in. While E9010 electrodes have been used successfully in Australia for thin wall (<0.250 in. [6.4 mm]), pipelines under ideal conditions (relatively flat terrain and relatively warm ambient temperatures), the use of these electrodes under other conditions should be avoided.

An alternative option to the use of an all-cellulosic SMAW procedure is the use of a so-called combination procedure, where cellulosic-coated SMAW electrodes are used for the root and hot passes, and a hydrogen-controlled welding process or consumable is used for the remainder of the passes. A much higher strength level can be achieved using a hydrogen-controlled welding process or consumable without the risk of weld metal hydrogen cracking. The most likely option for SMAW fill-and-cap passes in Grade X70 pipe is low-hydrogen vertical down (LHVD) SMAW. LHVD SMAW electrodes are available with strengths of 90 ksi (e.g., E9045) and 100 ksi (E10045) and are resistant to weld metal hydrogen cracking.

As an alternative to SMAW, the use of FCAW-G can be considered. Where possible, mechanized FCAW-G should be used in preference to semi-automatic (i.e., manually applied) FCAW-G. If manual FCAW-G is used careful control of the heat input is required.

Table 17 compares typical weld metal tensile properties, as quoted by the consumable manufacturer, for selected E6010, E8010, E9045, and E10045 SMAW welding consumables. The quoted values for E8010 indicate a typical tensile strength of 90 ksi. Assuming that the weld reinforcement (weld cap and weld root) may increase the strength of a girth weld by 5 - 10%, then a girth weld made with E8010 should have a tensile strength between 95 - 100 ksi. However, since most SMAW girth welds are made using E6010 for the root/hot pass, the tensile strength of an E6010/E8010 girth weld will be lower. As the pipe WT decreases and the proportion of the overall girth weld comprised of the E6010 root/hot pass increases, the tensile strength of the girth weld will decrease further.

Table 17. Typical SMAW Weld Metal Tensile Properties

Consumable	Consumable Designation	Yield Strength (ksi)	Tensile Strength (ksi)	Y/T
Lincoln Pipeliner 6P+	E6010	59 - 75	72 - 80	0.82
ESAB Pipeweld 6010 Plus	E6010	55	69 - 87	0.80
Hobart Pipemaster Pro-60	E6010	58	71	0.82
Lincoln Pipeliner 8+	E8010	69 - 79	81 - 97	0.83
Lincoln Shield Arc 70+	E8010	67 - 90	85 - 100	0.85
ESAB SureWeld 810P	E8010	72.7	88.3	0.82
Bohler Fox Cel 85	E8010	71	80 - 99	0.79
Bohler Fox Cel 80-P	E8010	71	80 - 99	0.79
Hobart Pipemaster 80	E8010	81	98	0.83
PhilArc PA-8010-G	E8010	74	92	0.80
Lincoln Pipeliner LH – D90	E9045	80 - 87	91 - 97	0.89
ESAB Pipeweld 90DH	E9045	85.6	97.2	0.88
Bohler Fox BVD 90	E9045	87	90 - 113	0.85
Lincoln Pipeliner LH-D100	E10045	90 -100	102 - 109	0.90
Bohler Fox BVD 100	E10045	97	100 - 130	0.90

During the JIP, discussions were held with a number of operators to review SMAW girth welding practices. Two operators confirmed that their standard SMAW welding practice requires E8010 welding consumables for the root and hot pass, and that this had not resulted in any pushback from the welding contractors. The use of E8010 consumables for the root/hot pass will increase the strength of the girth weld, particularly for thin wall pipelines.

The use of LHVD electrodes (E9045 or E10045) for the fill-and-cap passes will produce girth welds with increased strength. The use of E9045 LHVD electrodes, particularly the Bohler BVD 90 consumable, will produce weld metal with a tensile strength of around 100 ksi. LHVD consumables (E9045) have been used in several recent major Grade X70 pipeline projects and produced favorable results. These electrodes require some welder training, but the required technique is easily learned by pipeline welders who are accustomed to welding in the vertical-down direction. There are no additional equipment requirements, although there may be a need to upgrade welding machines from 200 A to 300 A. The use of low-hydrogen vertical-down (LHVD) electrodes can also increase productivity when compared to using cellulosic-coated electrodes.

7.3.4 FCAW Welding Consumables

FCAW can be used in semi-automatic mode (e.g., automatic wire feed but manual control of the welding torch) or be fully mechanized (e.g., bug and band system or chain driven system).

There are two broad categories of FCAW:

- Gas shielded FCAW (FCAW-G); and,
- Self-shielded FCAW (FCAW-S).

Gas shielded FCAW uses a shielding gas in addition to the flux and shielding provided directly by the welding wire. By comparison, self-shielded FCAW relies on the welding wire to provide both the flux and shielding.

Although FCAW-S is widely used in China for new pipeline construction, this process can produce inconsistent toughness properties and is prone to welding defects if used on a pipeline right-of-way (ROW) where adequate protection from the environment is not provided. For these reasons FCAW-S is not widely used for pipeline construction in North America. In addition, semi-automatic FCAW-S requires skilled welders.

FCAW-G has traditionally been used in North America for repair welding and tie-in welding. However, with the development of portable mechanized FCAW-G welding systems, it can now be considered a mainline welding procedure for small-to-medium diameter heavy wall pipelines or large diameter pipelines in regions with challenging ROWs (e.g., hilly or mountainous terrain).

In the fully mechanized mode, the FCAW-G power supply is controlled so the welding parameters are adjusted automatically as the bug welds around the pipe. Thus, fully mechanized FCAW can be operated by welding technicians as opposed to skilled welders. Other advantages of fully mechanized welding include higher productivity and increased consistency.

Mechanized FCAW-G requires welding shacks to protect the operator and welding system from the environment; therefore, this method requires side booms to lift and place the welding shacks.

For tie-in or mainline girth welds, FCAW-G is normally used to deposit fill-and-cap passes after depositing the weld root and hot pass with SMAW (normally E6010 root and either E6010 or E8010 hot pass). The combination process and, in particular, the SMAW root and hot pass, mean FCAW girth welds are normally fabricated to, and inspected to, workmanship criteria. Given the increased deposition rate from FCAW-G relative to SMAW, up to three SMAW passes (root, hot, and first fill) may be required before the first FCAW-G pass is deposited. As a result, there is a limiting pipe WT (around 10-12 mm) below which FCAW-G is not practical (i.e., if three SMAW weld passes are required before switching to FCAW-G, then the majority of the weld groove has already been filled before switching to FCAW-G, and the additional productivity from FCAW-G offers little advantage).

Alternatively, the root pass can also be deposited using a short-circuit controlled bead process – for example, Lincoln Surface Tension Transfer (STT), Fronius Controlled Metal Transfer (CMT), or Miller Regulated Metal Deposition (RMD). Although depositing the root pass with STT/CMT/RMD permits mechanized FCAW-G girth welds to be qualified to API 1104 Appendix A and inspected to ECA flaw acceptance criteria, it is still common practice to inspect FCAW-G girth welds where the root pass is deposited with STT/CMT/RMD to workmanship criteria.

Some operators are currently evaluating metal-cored arc welding (MCAW) wires deposited with a mechanized FCAW welding bug so that the same welding wire can be used to deposit the entire girth weld (e.g., root and hot pass followed by fill-and-cap passes). This would permit MCAW girth welds made with a single metal cored welding wire to be qualified to API 1104 Appendix A and inspected to ECA flaw acceptance criteria. This offers a major advantage if MCAW is considered for mainline girth welding.

There are a number of low hydrogen (4 to 5 ml/100 g of deposited weld metal) FCAW-G welding wires with strengths of 90 ksi or greater that are resistant to weld metal hydrogen cracking and have been used for welding fill-and-cap passes in recent Grade X70 pipeline projects. Examples include the ESAB Pipeweld FCAW-G wire, which is available as E91 T1, E101 T1, and E110 T1.

FCAW-G can be deployed using mechanized welding equipment or used in a semi-automatic (hand held) manner. Mechanized application results in higher productivity and benefits from close control of heat input, which results in less concern for HAZ softening when compared to semi-automatic application. When using self-shielded FCAW wires at these strength levels, the weld metal mechanical properties (strength and toughness) become very sensitive to welding parameters and, in particular, the weld cooling rate. With manual FCAW-G it is important to control heat input levels and set a maximum allowable heat input that is monitored and controlled during production welding.

Table 18 compares typical weld metal tensile properties for selected FCAW-G welding consumables. Mechanized FCAW girth weld procedures using E91 T1, E101 T1, and E110 T1 welding wires have been successfully deployed on several recent major US Grade X70 pipeline projects.

Table 18. Typical FCAW-G Weld Metal Tensile Properties

Consumable	Consumable Designation	Yield Strength (ksi)	Tensile Strength (ksi)	Y/T
Lincoln Pipeliner 81M	E81 T1	74 - 81	84 - 90	0.89
ESAB Pipeweld	E91 T1	88	97	0.91
ESAB Pipeweld	E101 T1	95	103	0.92
ESAB Pipeweld	E110 T1	110	122	0.90
Bohler T70P	E91 T1	80	93 - 119	0.75
Pinnacle	E81 T1	80	89	0.90

7.4 Transition Welds

One of the reported girth weld failures occurred at a transition weld where the thicker pipe was tapered down to the smaller pipe WT at the pipe end. Even with a taper ratio of 1:4, the transition joint will experience a stress concentration factor (SCF) from eccentricity caused by different pipe WTs.

The SCF at a transition girth weld is a function of the WT difference, length of the taper, and any high-low misalignment that may be present at the girth weld. However, SCFs between 1.50 to 2.00 would be typical for transition joints where the thicker pipe is transitioned to the thinner pipe at the girth weld (see Figure 7).

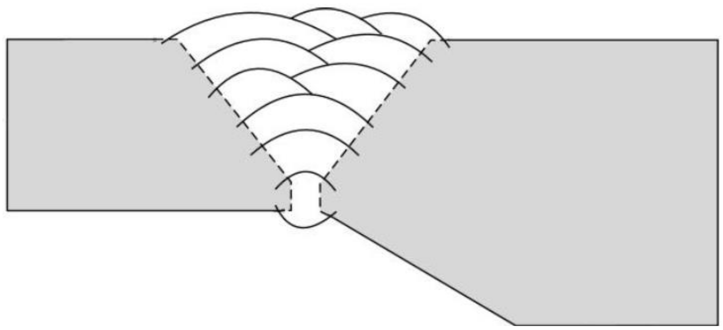


Figure 7. Schematic Showing Transition Weld with Taper at Pipe End

In the event of a local strain event at a transition girth weld, the strain will tend to focus in the thinner pipe WT due to the SCF which produce higher local strains at the girth weld due to the transition and the associated eccentricity.

When the stress at the girth weld exceeds the material yield strength, the application of an SCF is replaced by a strain concentration factor. After yielding occurs, the strain concentration can be approximated by calculating the square of the SCF (i.e., SCF^2). Thus, the strain concentration factor at a transition girth weld can be between 2.0 and 4.0, and clearly increases the risk of transition girth weld failures (particularly if the girth weld is under-matched or significant HAZ softening is present).

To reduce the potential for transition girth weld failures, it is recommended that, for transition girth welds between pipes of the same Grade, the thicker wall pipe is counter-bored so that the pipe on either side of the girth weld is the same thickness (for transition joints made between pipes of the same grade). A minimum counter-bore length of 6 in., followed by a taper of no more than 1:4 is recommended.

7.5 Recommendations

To facilitate girth weld over-matching in Grade X70 pipelines, the following recommendations are proposed for SMAW and SMAW/FCAW girth welds:

1. Girth weld procedures should be qualified on project pipe and ideally on pipe with longitudinal tensile properties that are at the upper range of the pipe order. In addition, consideration should be given to performing WPQ on pipe that has been subjected to an FBE thermal cycle to account for aging;
2. CWT tests shall be performed on specimens with the weld reinforcement in place;
3. CWT specimens should fail in the base pipe (i.e., failure in the girth weld or HAZ is not acceptable). In special cases, where CWT specimens fail in the weld region but *only* after significant deformation occurs in the parent pipe (i.e., gross section yielding occurs in the parent pipe), the suitability of the weld procedure can be assessed on a case-by-case basis;
4. Mainline pipe-to-pipe or tie-in girth welds should be made using SMAW LHVD (e.g., E9045) or FCAW-G (e.g., E91 T1) consumables for the fill-and-cap passes;
5. SMAW procedures using E6010 for the root/hot pass and E8010 for the fill-and-cap passes should be limited to pipe assemblies and station piping.
6. Transition welds should be made between pipe of the same grade, with the thicker pipe counter-bored to the thickness of the thinner pipe.

8 HAZ Softening

8.1 General

The main goal of developing supplementary line pipe performance requirements on HAZ softening susceptibility is to mitigate (limit) HAZ softening in girth welds.

The thermal cycles produced during girth welding cause the pipe material on either side of the weld to undergo changes in microstructure and material properties from exposure to high temperatures. In TMCP steels, the HAZ generally contains regions where the:

- Hardness is increased due to transformation hardening in the Coarse Grain Heat Affected Zone (CHAZ) and precipitation; and,
- Hardness is reduced due to transformation softening.
- Hardness is increased due to precipitation hardening.

Figure 8 illustrates a typical schematic hardness profile across the HAZ of TMCP steel.

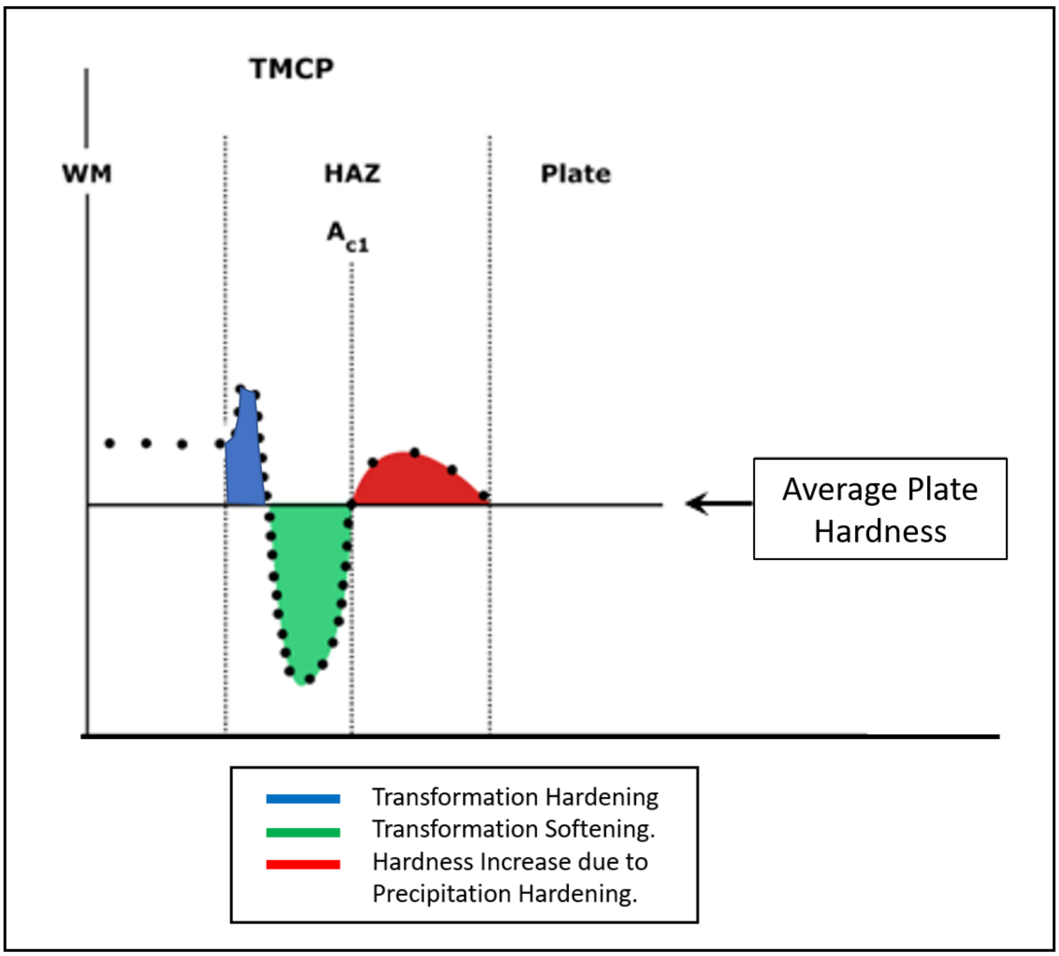


Figure 8. Schematic of Hardness Variation across the Heat Affected Zone

The size (width) of the HAZ is primarily a function of weld heat input and the cooling rate. Increasing the heat input increases the width of the HAZ. Increased cooling rates decrease the width of the HAZ.

The weld cooling rate is frequently characterized by a parameter that defines the time for the weld metal to cool from 800 to 500°C ($t_{8/5}$). In general:

- As $t_{8/5}$ increases (e.g., high heat input, high preheat temperature or welding a thin wall pipe), the HAZ width increases and the maximum and minimum HAZ hardness' decrease; and,
- As $t_{8/5}$ decreases (low heat input, low preheat temperature or welding a thick wall pipe) the HAZ width decreases, and the maximum and minimum HAZ hardness' increase.

With respect to HAZ strength, the main concern is HAZ softening. In particular, when a region of the HAZ exhibits lower strength than both the parent pipe and the girth weld – resulting in local strain accumulation in the softened HAZ. Clearly, the effect of HAZ softening will increase as the degree of HAZ softening and the width of the softened HAZ increase.

As noted earlier, the effect of HAZ softening is also dependent on weld geometry. Since shear bands form at an angle of 45°, failures from HAZ softening are more likely to occur in SMAW or FCAW girth welds with wide bevel angles, instead of mechanized GMAW welds that tend to have near-vertical sidewalls, i.e., the effect of HAZ softening.

- Increases as the weld bevel angle increases and,
- Decreases as the weld bevel approaches a vertical or near vertical sidewall (.

While the minimum HAZ hardness is an important parameter, the structural performance of a softened HAZ and the potential for local strain accumulation in the softened HAZ is more dependent on the degree of HAZ softening relative to the parent pipe and weld metal [15–19]. For example, a minimum HAZ hardness of 180 HV10 in a pipe material with an average hardness of 200 HV10 (i.e., 10% softening) is less severe than a minimum HAZ hardness of 200 HV10 in a pipe material with an average hardness of 240 HV10 (i.e., 20% softening).

For a given weld heat input and cooling rate, the minimum HAZ hardness is primarily a function of the chemical composition of the steel. However, comparatively, the initial parent pipe hardness is a function of:

- Chemical composition;
- Original steel manufacture TMCP parameters (e.g., rolling practice, water cooling rates, etc.);
- Pipe forming / expansion strains; and,
- Strain aging response of the pipe material.

Although it may be feasible to develop a correlation between minimum HAZ hardness and chemical composition, it is unrealistic to expect a perfect correlation between HAZ softening and chemical composition.

8.2 HAZ Hardness Correlations

There has been extensive research over the last 50 years in developing parameters to predict how a material responds to welding and, in particular, predict the hardness of the CGHAZ material. The primary driver of this work was to produce a parameter that could be used to help mitigate HAZ hydrogen cracking.

The general method of characterizing susceptible HAZ microstructures is based on HAZ hardness. The harder the HAZ, the more susceptible the HAZ is to hydrogen cracking. The hardness of a weld HAZ is a function of the parent steel chemical composition and the HAZ cooling rate. HAZ transformation behavior can be assessed using a parameter called the Carbon equivalent (CE).

CE formulae were originally developed to give a numerical value for a steel composition in which the contributions of the elements that contribute to HAZ hardness and the possible formation of martensite are summed to give a measure of the overall transformation temperature of the steel during rapid cooling following welding. These formulae were later extended to represent the contribution of the composition to the HAZ hydrogen cracking susceptibility of steel and provide a measure of weldability.

HAZ hardness can be controlled by:

- Specifying the parent steel chemistry (limiting the carbon and CE); and,
- Specifying heat input ranges, and pre-heat and interpass temperature requirements to control the weld cooling rate. Specifying pre-heat and interpass temperature requirements will also assist with hydrogen diffusion.

There are a number of CE formulae to assess material hardenability and weldability. The two most common equations are the Lloyds CE equation, which was adopted by the *International Institute of Welding* (IIW), and is commonly referred to as $CE_{IIW,}$ and the Pcm equations. The Pcm equation, which was developed by Ito and Bessyo[20], is the preferred equation for low carbon steels (C <0.10%). See Equation 1 and Equation 2 for the IIW and Pcm CE equations, respectively.

Equation 1. IIW Carbon Equivalent Formula

$$\boldsymbol{CE_{IIW} = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15}} \quad (1)$$

Equation 2. Pcm Carbon Equivalent Formula

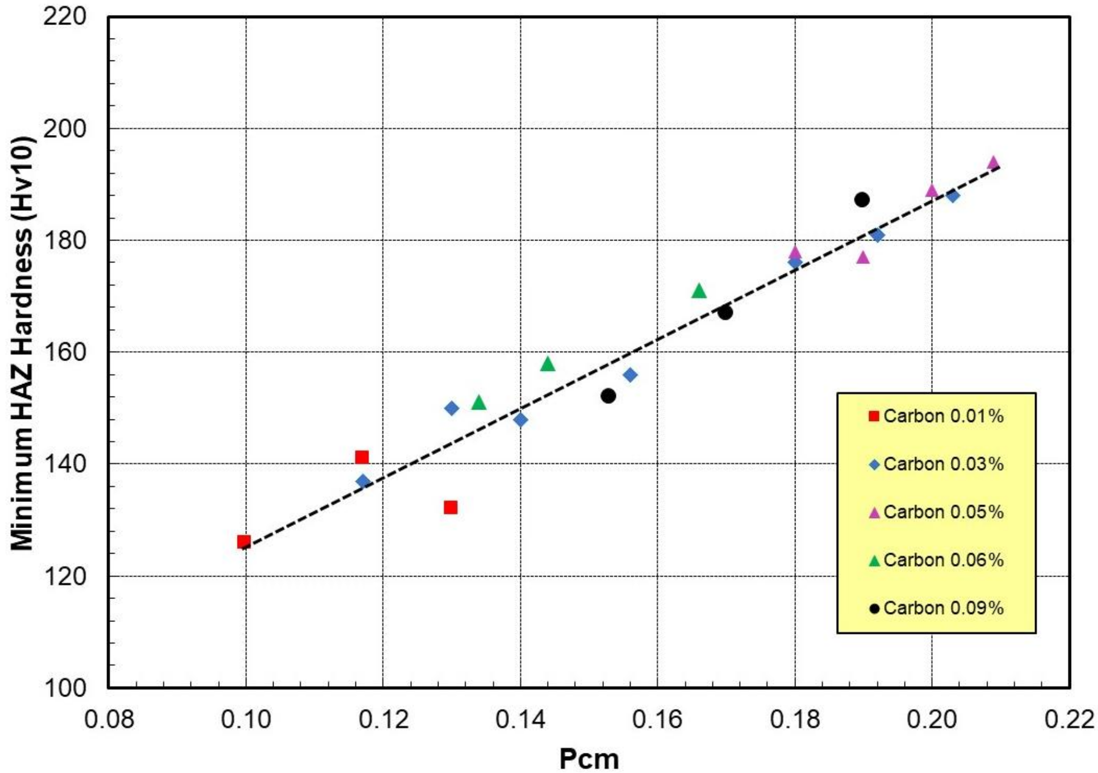
$$\boldsymbol{P_{cm} = C + \frac{Si}{30} + \frac{Mn+Cu+Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B} \quad (2)$$

Although the Pcm parameter has received broad acceptance, the Pcm formula does not include all the elements that may impact transformation behavior (e.g., Pcm does not include niobium or titanium which are present in almost all Grade X70 alloy designs).

Figure 9 presents data obtained from an experimental study[21] that compares minimum HAZ hardness against the Pcm parameter for a range of steels (not pipeline steels). The upper plot in Figure 9 presents the hardness data as a function of Pcm. The lower plot presents the same data as a function of carbon content. Although the data in Figure 9 contains results for 0.01% carbon steel, the range of Pcm values studied at this ultra-low carbon level is extremely limited because carbon is the dominant term in the Pcm equation. The results show that, at a carbon level of 0.03%, a much larger range of Pcm values was obtained.

It is clear from Figure 9 that, although there is a clear correlation between minimum HAZ hardness and Pcm, there is no clear correlation between minimum HAZ hardness and carbon content with the results exhibiting significant scatter and no obvious trend. Although some operators currently include minimum (and maximum) limits on carbon (typically 0.04%) minimum, due to concerns regarding HAZ softening, there is no consistent evidence to support the view that a low carbon content, by itself, will result in excessive HAZ softening. Indeed, there are many pipelines in operation in North America with carbon levels less than 0.04%

If, in Figure 9, a HAZ hardness of 150 HV_{10} is set as a reasonable minimum allowable value, which corresponds to a HAZ hardness 20% less than that obtained for a high carbon (0.09%) high Pcm (0.21) steel, then the data suggests a minimum Pcm value of 0.14. Also, although there is much more scatter in the lower plot where HAZ softening is plotted against Carbon (%), it appears that only steels with C ≤ 0.03 had minimum HAZ hardness' below 150 HV_{10}.



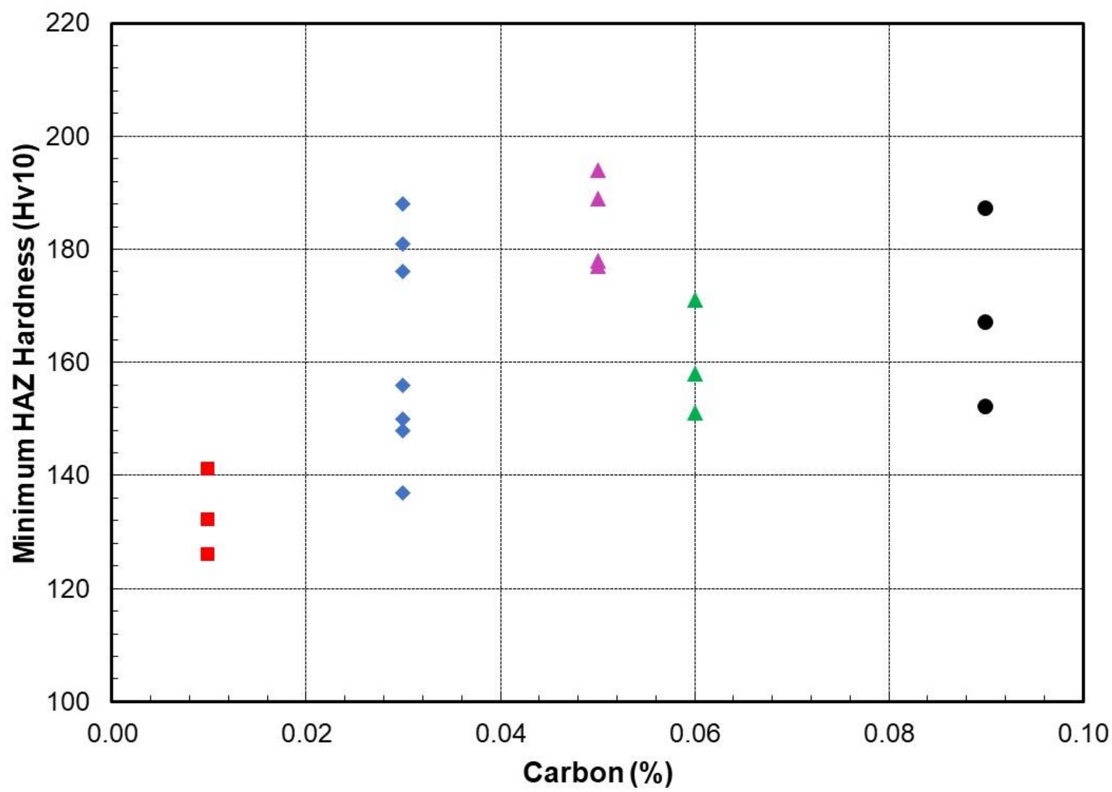


Figure 9. Plots of Minimum HAZ Hardness vs. Carbon (%) and Pcm

8.3 Mitigation of HAZ Softening

As noted earlier, although the minimum HAZ hardness is an important parameter –the structural performance of a girth weld HAZ and the potential for local strain accumulation in the softened HAZ region is more dependent on the degree of HAZ softening relative to the parent pipe and weld metal.

The initial hardness of the parent pipe is dependent on a number of variables, including:

- Chemical composition;
- TMCP parameters;
- Pipe forming strains; and,
- Strain aging.

Thus, CE, which was originally developed to assess CGHAZ transformation characteristics (CGHAZ hardness), may not be a suitable parameter to predict HAZ softening.

8.4 Bead on Pipe HAZ Hardness Test Program

In Phase 2 of the JIP, one of Tasks included a series of bead on pipe (BOP) tests to evaluate HAZ softening in a range of Grade X70 pipe materials. The major objectives of this task are summarized as follows:

- Determine HAZ softening susceptibility of Grade X70 pipe and determine if can be correlated with pipe chemistry including Carbon and Pcm etc.;
- Develop recommendations on chemical composition limits for Grade X70 pipe to mitigate HAZ softening (e.g., minimum Pcm value); and,
- Determine the effect of pre-heat on HAZ softening.

BOP tests were performed on 11 API 5L Grade X70 pipe materials and a low Mn Grade X65 pipe material with a very low Pcm. Details of the pipe materials, which were donated by JIP sponsors, are presented in Table 19. The pipe materials had the following Carbon and Pcm ranges:

- Grade X70M only:
  - Carbon: 0.038% min. to 0.087% max.; and,
  - Pcm: 0.122 min. to 0.201 max.
- All pipe materials (including low Mn):
  - Carbon: 0.038% min. to 0.087% max.; and,
  - Pcm: 0.108 min. to 0.201 max.

Table 19. Details of BOP Pipe Materials

Pipe Grade	Nominal OD (inches)	Nominal Wall (inches)	Seam Weld	EWI Sample Number
API 5l X70M	36	0.438	SAWH	17967
	36	0.375	SAWH	17968
	30	0.625	SAWH	17969
	30	0.476	SAWH	17970
	30	0.375	SAWH	17971
	30	0.375	SAWH	17972
	48	0.689	SAWH	17973
	30	0.476	SAWH	18023
	24	0.340	ERW	18024
	48	0.614	SAWH	18047
Low Mn	20	0.750	SAWL	17984

The low Mn steel, which is a Grade X65 pipe material, as opposed to Grade X70, was selected for the BOP test program because it has a very low Pcm. Table 20 presents the full chemical compositions of BOP pipe materials.

Table 20. Chemical Compositions of BOP Pipe Materials

Element	17967	17968	17969	17970	17971	17972	17973	18023	18024	18047	58003	17984
C	0.0670	0.0630	0.064	0.047	0.069	0.065	0.052	0.043	0.038	0.087	0.065	0.046
Mn	1.5800	1.5600	1.57	1.62	1.33	1.29	1.67	1.52	1.48	1.67	1.59	0.36
Si	0.2700	0.2400	0.26	0.26	0.29	0.25	0.26	0.17	0.19	0.29	0.22	0.14
P	0.0090	0.0080	0.008	0.014	0.006	0.006	0.007	0.017	0.014	0.010	0.015	0.010
S	0.0000	0.0000	0.001	0.003	0.004	0.002	0.002	0.002	0.001	0.001	0.002	0.004
Cr	0.1970	0.1920	0.183	0.260	0.261	0.242	0.023	0.187	0.032	0.053	0.021	0.399
Ni	0.0060	0.0050	0.016	0.108	0.008	0.009	0.024	0.011	0.002	0.130	0.018	0.132
Mo	0.0000	0.0000	0.078	0.053	0.000	0.003	0.000	0.003	0.001	0.027	0.010	0.006
Cu	0.0180	0.0390	0.017	0.383	0.021	0.025	0.012	0.038	0.013	0.116	0.008	0.237
V	0.0430	0.0430	0.043	0.001	0.053	0.046	0.003	0.002	0.000	0.002	0.001	0.002
Al	0.0460	0.0380	0.042	0.031	0.023	0.024	0.037	0.037	0.046	0.041	0.028	0.044
Ti	0.0200	0.0180	0.020	0.014	0.010	0.008	0.020	0.016	0.019	0.030	0.015	0.014
Nb	0.0730	0.0700	0.083	0.092	0.069	0.062	0.131	0.102	0.102	0.065	0.071	0.081
Co	0.0000	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Tungsten	0.0000	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sn	0.0000	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.009
Boron	0.0004	0.0004	0.0003	0.0003	0.0005	0.0002	0.0004	0.0003	0.0002	0.0008	0.0001	0.0001
Zr	0.0000	0.0000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000
Pcm	**0.1724**	**0.1671**	**0.1730**	**0.1794**	**0.1675**	**0.1574**	**0.1493**	**0.1384**	**0.1218**	**0.2011**	**0.1554**	**0.1078**

Although the steels listed above, which were provided by JIP sponsors, cover a range of chemical compositions they do not cover the entire range of Grade X70 alloy designs.

Figure 10 presents a plot of carbon (%) vs. Pcm for all the pipe materials. Since the Pcm equation is dominated by the carbon content, a reasonable correlation between carbon content and Pcm is expected. It is evident from Figure 10 that the low Mn steel lies well outside the trend for the Grade X70 pipe materials. The Grade X70 pipe material with a carbon content of 0.047% and a Pcm of 0.179 (circled in Figure 10) has 0.383% Cu which is much higher than all the other Grade X70 pipe materials (0.009% to 0.116%). This is typical of a steel made using an Electric Arc Furnace (EAF). In addition, this material has 0.26% Cr and 0.108% Ni – revealing that low Carbon steels are not necessarily low Pcm steels.

It is also worth noting that Steel 18047, which has a carbon content of 0.087% (highest Carbon % tested) also appears to have a boron addition. Ti-B steels are not typical of modern pipeline steels. The presence of boron may result in poor HAZ toughness.

Ideally BOP tests should be performed on material with the same WT to ensure a consistent heat sink and cooling rate. However, this was not possible given the plan to test the actual Grade X70 pipe materials provided by the JIP Sponsors, which had a range of alloy designs, chemical compositions, and WTs.

Single weld pass BOP specimens were fabricated with heat inputs of 0.5, 1.0, and 2.0 kJ/mm using an E8010 welding consumable. After the BOP welds were deposited, a macro sample was extracted from each weld in each panel for macro and hardness testing. The macro samples were photographed prior to and after automated hardness testing using an automatic hardness testing machine and a 1 kg load. Figure 11 is a plot of a sample macro taken after microhardness testing.

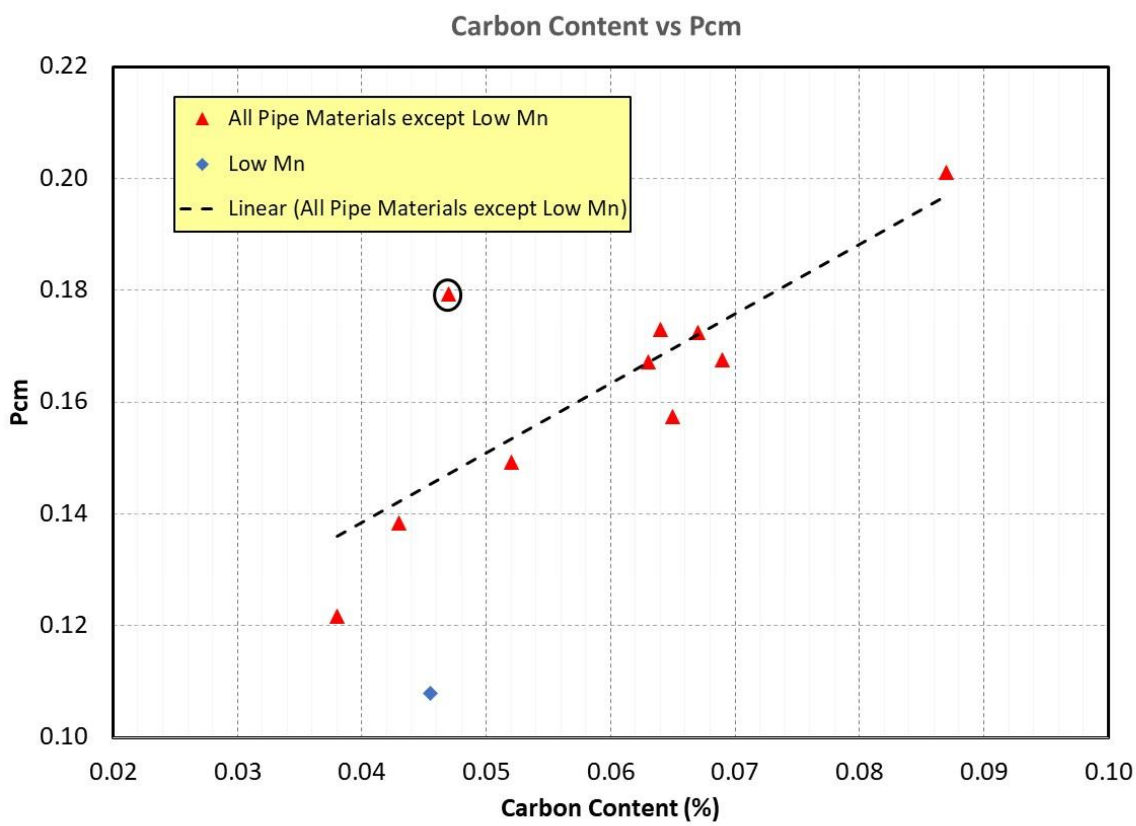


Figure 10. Plot of Carbon Content (%) vs. Pcm for BOP Pipe Materials

The circled data point in Figure 10 has high residuals of Cr, Cu, and Ni.

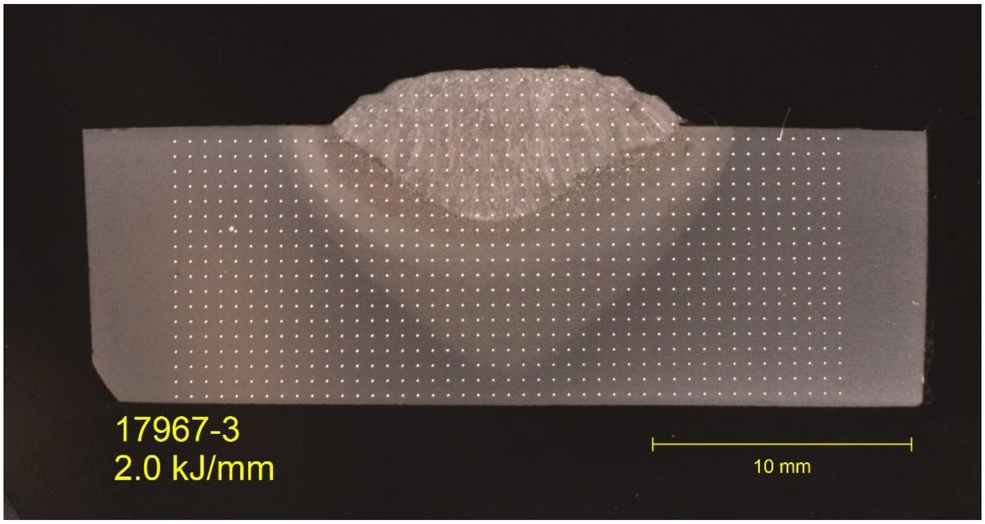


Figure 11. Typical Macro after Microhardness Testing (2.0 kJ/mm)

The BOP results were captured electronically and processed as follows:

- Color fringe plots showing the variation in hardness in the BOP sample; and,
- An Excel spreadsheet for detailed analysis of individual or groups of hardness scans.

Although the color fringe plots provided an overall image of the hardness variation in the BOP sample (i.e., pipe, weld, and HAZ), the detailed analysis of the BOP tests relied on analyzing individual hardness scans. These hardness scans were selected and compiled for analysis:

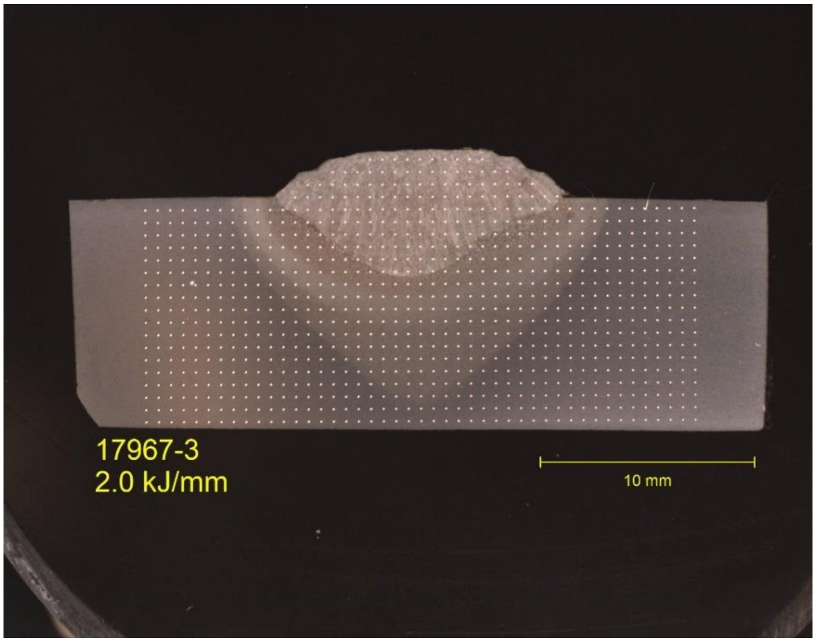
- 0.5 and 1.0 kJ/mm: First three scans from OD; and,
- 2.0 kJ/mm: First five scans from OD.

To minimize the effect of different WT samples and associated variation in cooling rates, the hardness scans were taken close to the surface of the BOP specimens. Although the hardness surveys were taken close to the surface of the BOP hardness to minimize the effect of pipe WT, the results may still exhibit a thickness effect due to the increase in heat sink capacity with increasing WT.

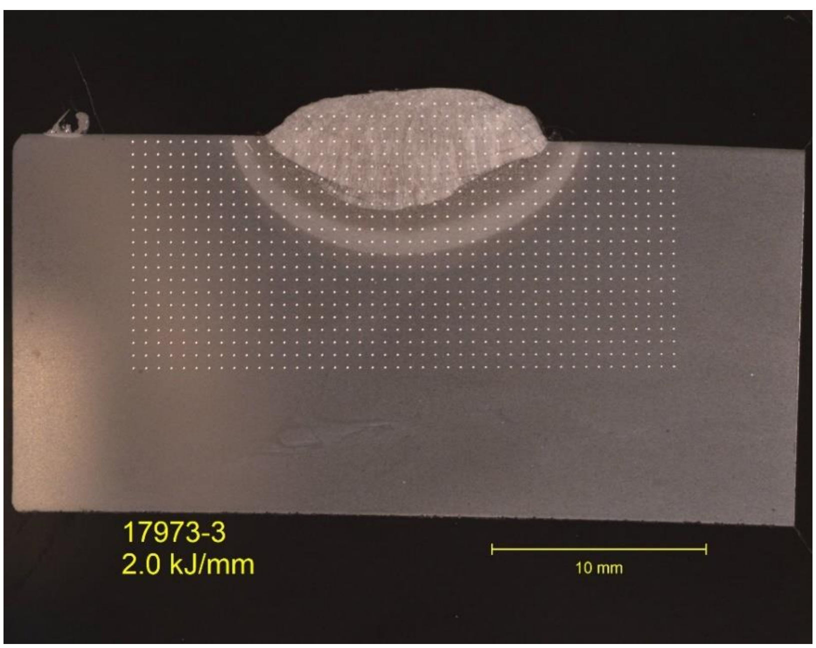
As the pipe WT increases the heat flow or cooling rate changes from 2D Heat Flow to 3D Heat Flow. This can affect both the width of the HAZ region as well as the HAZ microstructure and the degree of HAZ softening. The effect of increasing pipe WT on the HAZ width can be seen in Figure 12 which compares photographs of two BOP samples both made at 2.0 kJ/mm. Sample 17967 is a 36″ x 0.438″ SAWH pipe. Sample 17973 is a 48″ x 0.689″ SAWH pipe.

It is clear from Figure 12 that the HAZ widths at the bottom of the BOP weld (i.e., the 6 o'clock location) are very different for the two samples with a much smaller HAZ width for the thicker BOP sample (17973) than the thinner pipe sample (17967). This difference in HAZ width is due to 3D Cooling which increases with increasing pipe WT but also with increasing distance from the pipe free surface. In comparison the widths of the HAZ close to the free surface of the pipe are very similar confirming that at the BOP pipe surface the cooling rate is not affected to anywhere near the same level as the bottom of the BOP weld.

This effect is confirmed in Figure 13 which presents plots of HAZ width (2.0 kJ/mm) at the bottom of the BOP weld (6 o'clock) and the HAZ widths close to the free surface (3 and 9 o'clock) where the BOP hardness scans were taken. It is clear from the upper plot in Figure 13 that the HAZ widths at the bottom of the BOP weld exhibit a strong function of the pipe WT. In comparison the HAZ widths close to the free surface do NOT display a strong dependence on pipe WT confirming that 3D Heat Flow is not dominant close the free surface. This is similar to the conditions of plane stress and plane strain in a fracture toughness specimen where close to the free surface there is a state of 2D constraint but as you move through the specimen thickness the constraint transitions to 3D constraint.

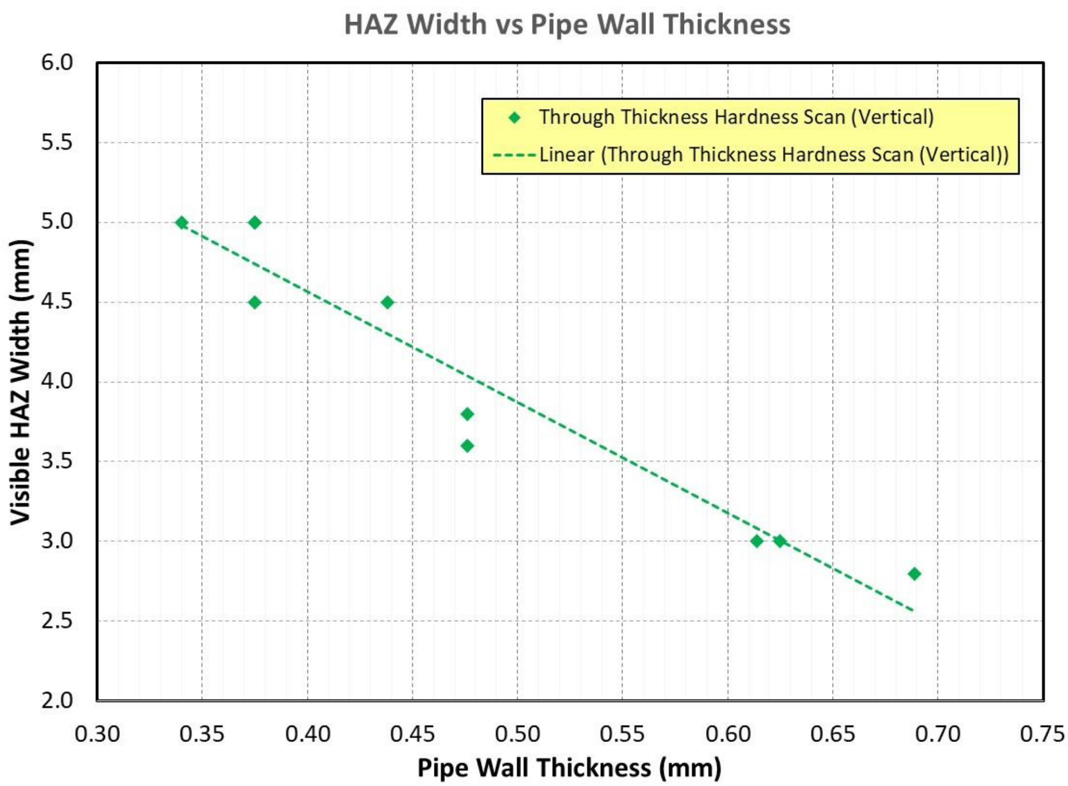


Sample 17967: 36" x 0.438"



Sample 17973: 48" x 0.689"

Figure 12. Comparison of BOP Macros (2.0 kJ/mm) for BOP Samples 17967 and 17973



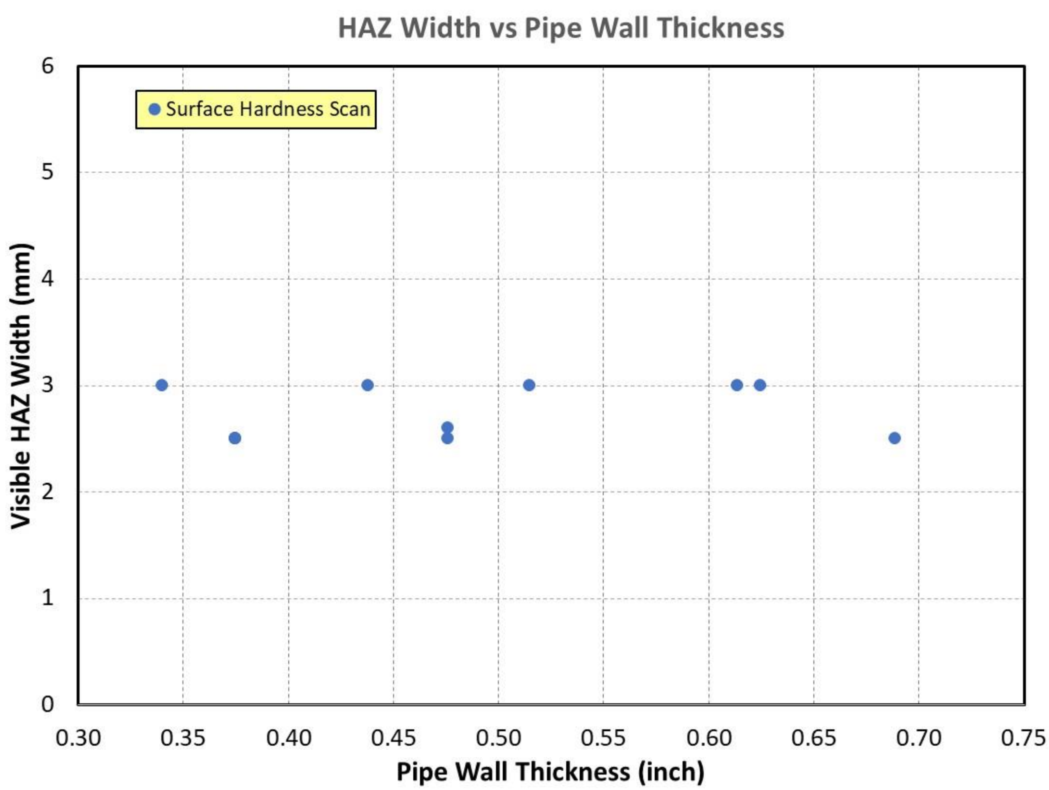


Figure 13. Comparison of Bead on Pipe HAZ Widths vs Pipe WT (2.0 kJ/mm)

For each scan, the data were analyzed to determine the following parameters:

- The average parent pipe hardness outside the HAZ;
- The minimum HAZ hardness;
- The maximum HAZ hardness;
- Maximum HAZ Softening (%) : Min. HAZ Hardness vs. Average Pipe Hardness; and,
- Max. HAZ Softening (Hv) : Min. HAZ Hardness vs. Average Pipe Hardness.

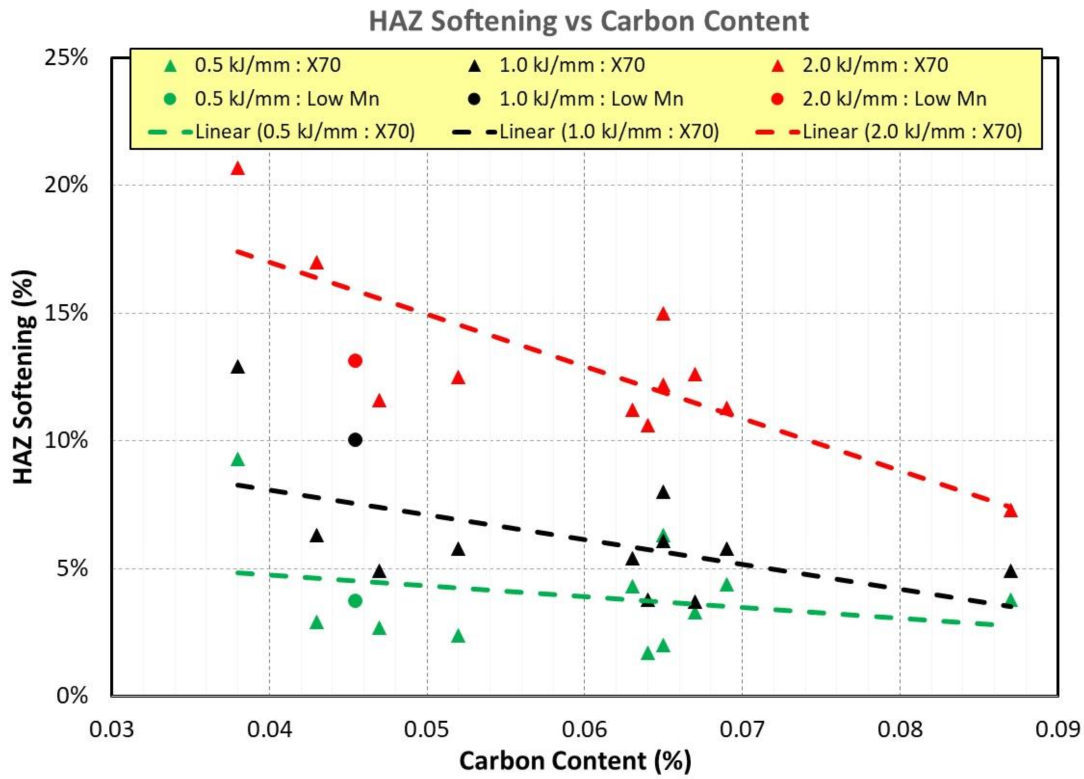
These parameters were then averaged (three scans for 0.5 and 1.0 kJ/mm, and five scans for 2.0 kJ/mm) to screen out individual anomalous results. Table 21 presents a typical set of results for a 2.0 kJ/mm sample, which shows extremely consistent results.

Table 21. Example HAZ Softening Results (Sample 2.0 kJ/mm)

Scan	Min. HAZ Hardness	Max. HAZ Hardness	Average Pipe Hardness	HAZ Softening (Hv)	HAZ Softening (%)
1	190	249	217	27.0	12.4
2	194	246	222	28.0	12.6
3	196	243	224	28.3	12.6
4	196	241	224	28.8	12.8
5	195	240	224	28.7	12.8
Average	**194**	**244**	**222**	**28.2**	**12.7**

Figure 14 presents the results of the BOP tests as plots of HAZ Softening (%) vs. Carbon (%) and Pcm. The results confirm that HAZ softening is very dependent on heat input. For heat inputs of 0.5 and 1.0 kJ/mm, the HAZ softening was generally less than 10%. At a heat input of 2.0 kJ/mm, HAZ softening up to 20% occurred.

The 0.038% Carbon steel, which exhibited HAZ softening of more than 20% at a heat input of 2.0 kJ/mm, is a very low manganese steel with virtually no residuals to add strength. It is a very lean analysis, even for a higher niobium Grade X70 steel.



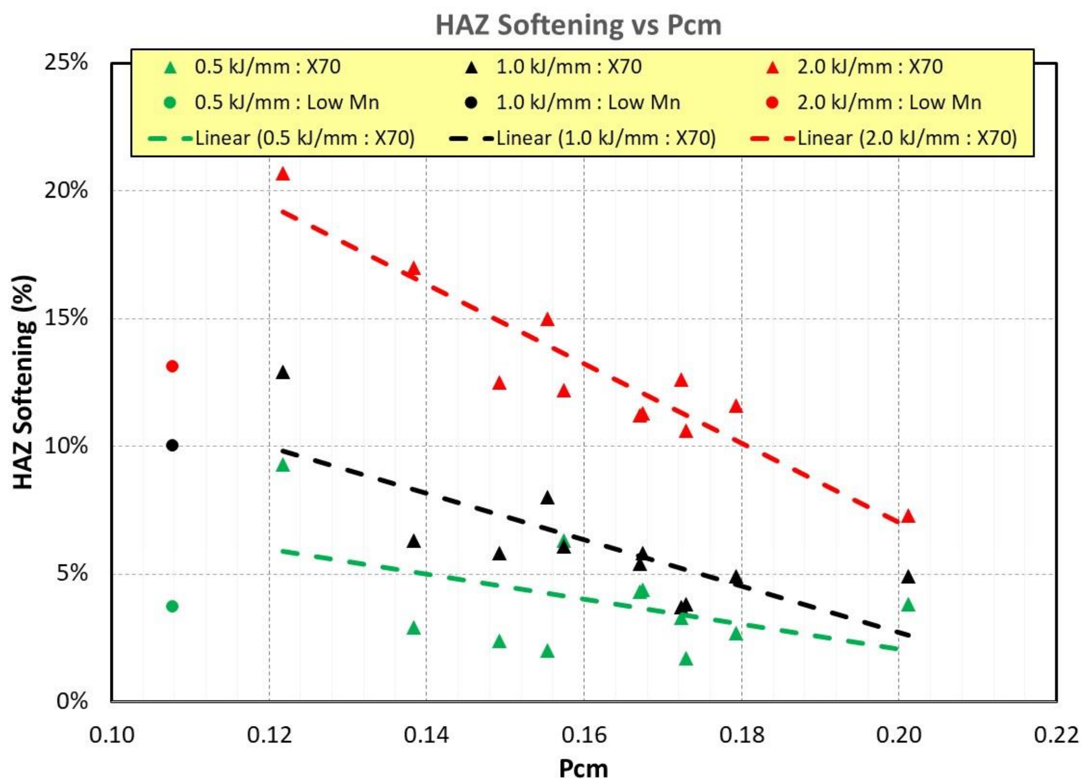


Figure 14. HAZ Softening (%) vs. Carbon (%) and Pcm

Although Figure 14 includes the results from the low Mn steel, the results of the low Mn steel were not used when establishing fits to the data. This steel, which is closer to Grade X65 than Grade X70, was selected because it has a very low Pcm value. However, the results obtained from this steel, which was developed for sour service application and would not be considered for a cross-country pipeline, do not follow the trends from the 11 Grade X70M pipe materials tested. Thus, the Project Technical Team excluded the low Mn results from the X70 data set. Figure 14 contains linear fits to the Grade X70 data (0.5, 1.0 and 2.0 kJ/mm). Table 22 presents the R^2 values for the fits.

Table 22. R^2 Values for Linear Fits to HAZ Softening Plots

Chemical Composition Parameter	Heat Input (kJ/mm)		
	0.5	1	2
Carbon (%)	0.071	0.285	0.639
Pcm	0.226	0.578	0.866

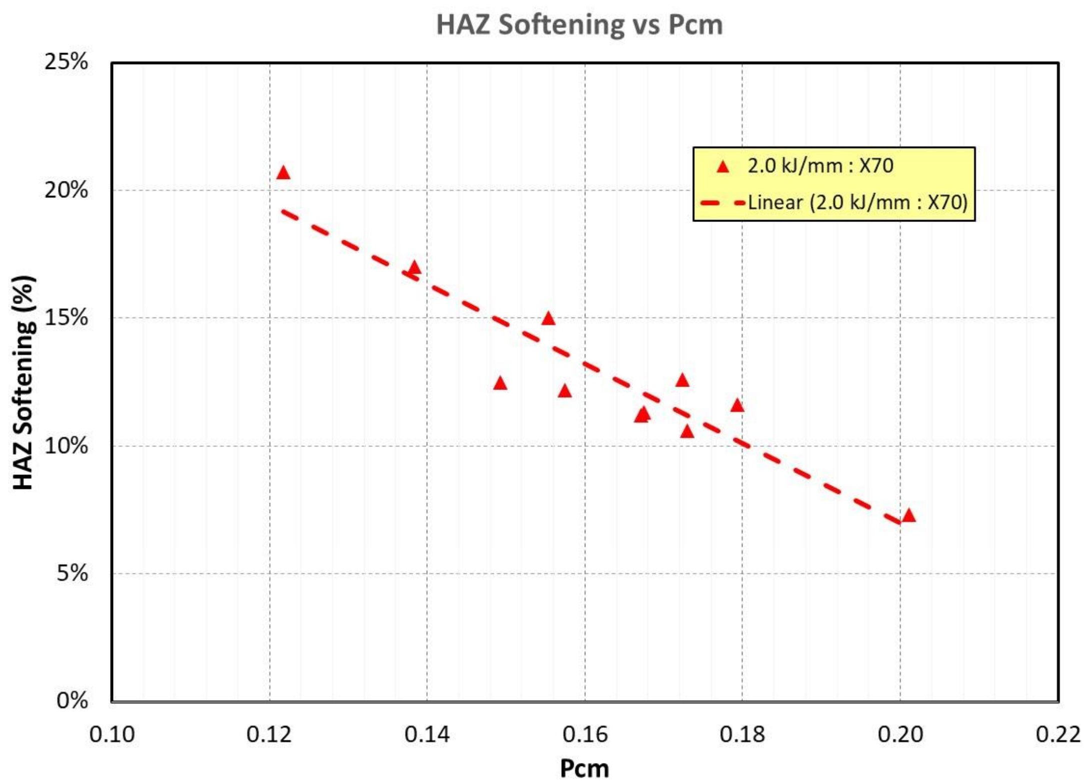
The parameter R^2 is a statistical measure of how close the data are to the fitted regression line. It is also known as the *coefficient of determination* or the *coefficient of multiple determination for multiple regression*.

The value of the parameter R^2 is always between 0 and 1. An R^2 value of 0 indicates that the fit explains none of the variability of the response data around its mean. In comparison an R^2 value of 1 indicates that the fit explains all the variability of the response data around its mean.

In general, the higher the R^2, the better the model fits the data. In Table 23, the R^2 values >0.5 are highlighted in yellow because these represent reasonable fits. As noted previously, it is unrealistic to assume a perfect correlation between carbon (%) or Pcm and HAZ Softening (%). This is because the final HAZ hardness is primarily a function of chemical composition. However, the initial pipe hardness is dependent on a number of factors. Nevertheless, the correlation between HAZ softening and Pcm is reasonably good – particularly at higher heat inputs. It is also clear that HAZ Softening (%) correlates better with Pcm than carbon.

As noted earlier the BOP tests were performed on pipe samples with a range of wall thickness (WT = 0.340” to 0.689”) and consequently the results may be influenced by pipe wall thickness. The HAZ softening results obtained at 2.0 kJ/mm are presented in Figure 15 as a plot of HAZ Softening (%) vs. Pcm. The upper plot in Figure 16 includes all the Grade X70 Bead on Pipe results (WT = 0.340” to 0.689”). The R^2 value for the fit is 0.866 which indicates a strong correlation. In the lower plot in Figure 16 the data is separated into two groups:

- WT < 0.500”
- WT > 0.500”



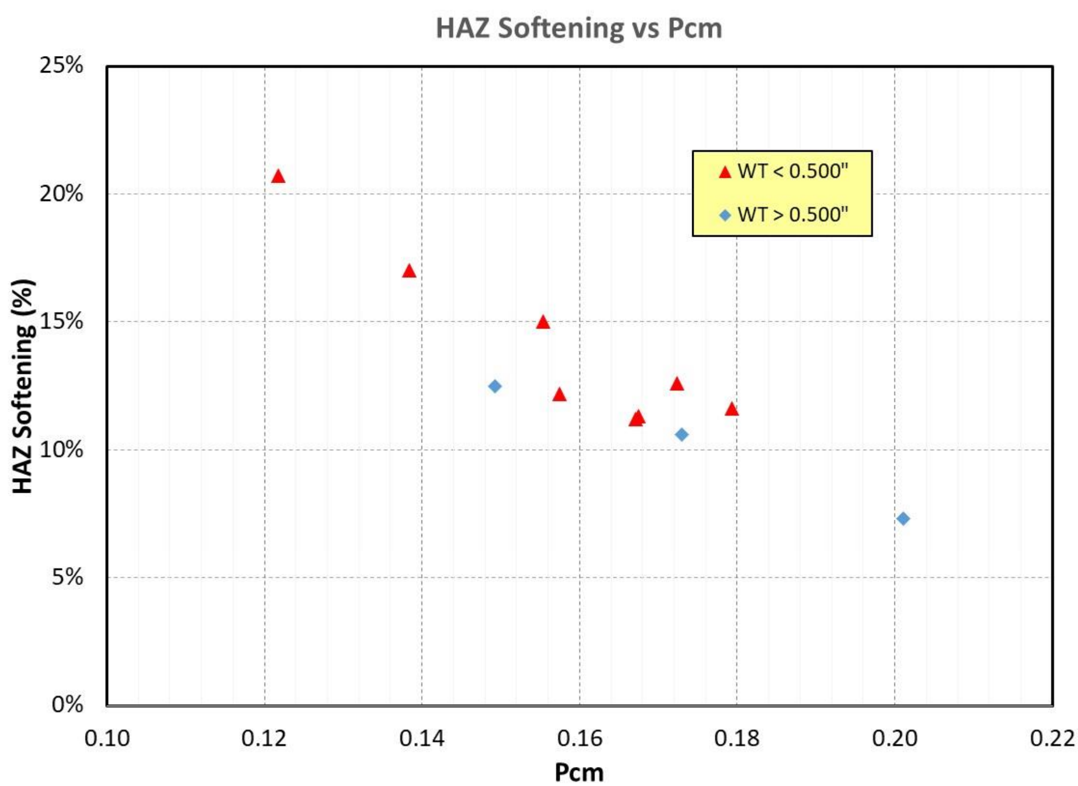


Figure 15. HAZ Softening (%) vs. Pcm

The lower plot confirms that the results from the heavy WT pipe samples (WT = 0.614", 0.625" and 0.689") follow the same general trend as the results for WT < 0.500" indicating that the results do not appear to exhibit a significant thickness effect. As noted previously, the hardness scans for the Bead on Pipe tests were deliberately taken close to the pipe surface to minimize the impact of pipe WT. The lower plot in Figure 16 would suggest that this approach was successful.

Figure 16 presents the results of the BOP Tests at 2.0 kJ/mm as a plot of HAZ Softening vs. Average Parent Pipe Hardness. It is clear from Figure 16 that the only two cases where HAZ Softening was >15% were in pipe materials with parent pipe hardness' greater than 230 HV_1. However, there were other pipe materials with hardness >230 HV_1 that exhibited HAZ softening in the range 10-12% confirming that high initial parent pipe hardness is not a reliable indicator of pipe materials that have a higher susceptibility to HAZ softening. Indeed, the results in Figure 16 do not show a clear trend between HAZ softening and initial pipe hardness.

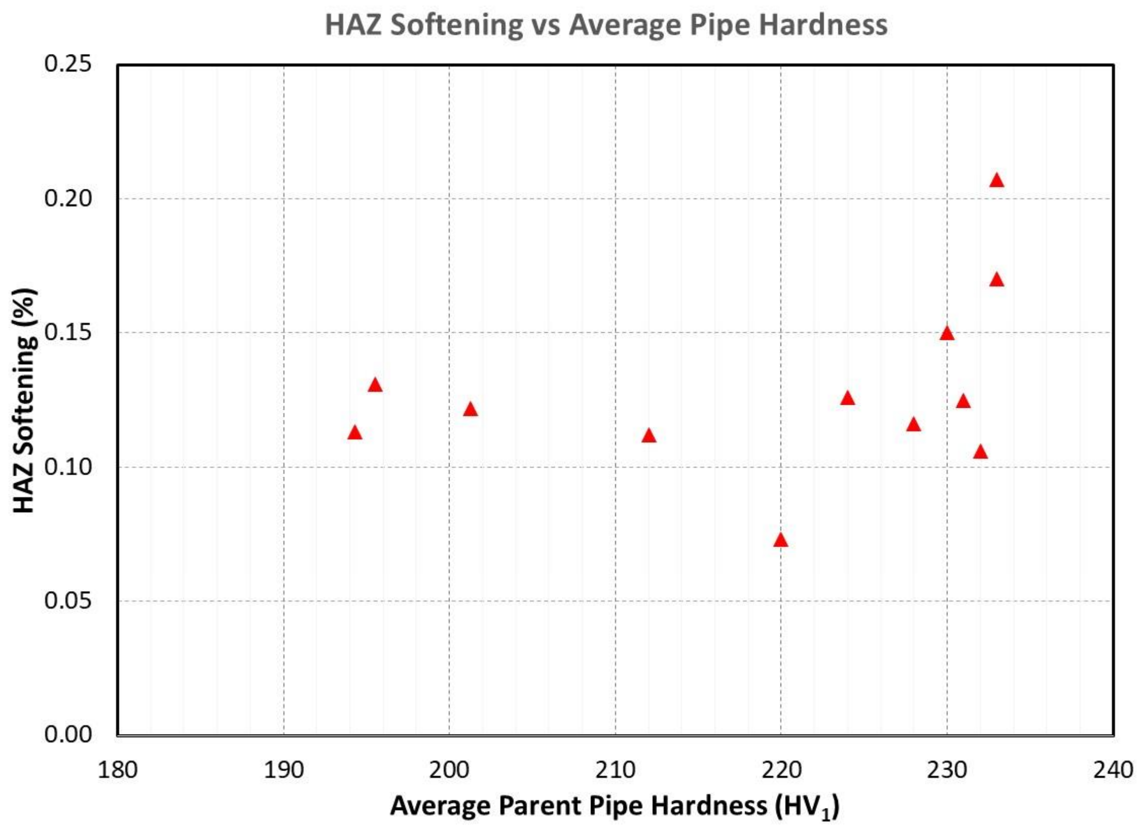


Figure 16. HAZ Softening (%) vs. Average Pipe Hardness

In addition, to the degree of HAZ softening (i.e., HAZ Softening %) the width of the HAZ and in particular the width of the softened HAZ region is important. Table 23 summarizes the following HAZ widths:

- Widths of the visible HAZ determined from the macros;
- Width of the HAZ determined from the hardness scan; and,
- Width of the softened HAZ determined from the hardness scans.

Table 23. HAZ Widths Determined from Macros and Hardness Scans

Material	Pcm	Heat Input (kJ/mm)	HAZ Width Macro (mm)	HAZ Width Hv (mm)	Width Soft HAZ (mm)	HAZ Softening (%)	Average Pipe Hardness	Min HAZ Hardness
17967	0.172	0.5	2.0	2.0	0	3.3	220	213
		1	2.0	2.0	1	3.7	224	216
		2	3.0	3.0	1.5	12.6	224	196
17968	0.167	0.5	1.5	2.0	0.75	4.3	223	212
		1	2.0	2.0	1	5.4	222	210
		2	2.5	3.0	4	11.2	212	187
17969	0.173	0.5	1.5	1.5	0.75	1.7	225	218
		1	2.0	1.5	2	3.8	230	221
		2	3.0	4.0	3	10.6	232	207
17970	0.179	0.5	1.5	1.5	0	2.7	226	220
		1	2.0	2.0	1	4.9	228	217
		2	2.6	2.5	1.5	11.6	228	201
17971	0.167	0.5	1.5	2.0	0.5	4.4	194	185
		1	2.0	3.0	2	5.8	189	179
		2	2.5	3.5	2.5	11.3	194	174
17972	0.157	0.5	1.5	2.0	0.5	6.3	205	192
		1	2.0	2.0	1	6.1	200	188
		2	2.5	4.0	3	12.2	201	177
17973	0.149	0.5	1.0	1.0	0	2.4	228	222
		1	2.5	2.0	1	5.8	229	217
		2	2.5	3.0	2.5	12.5	231	207
18023	0.138	0.5	1.0	2.0	0.75	2.9	233	226
		1	2.0	2.5	1	6.3	231	215
		2	2.5	3.0	2	17	233	194
18024	0.122	0.5	1.5	2.0	1.5	9.3	243	219
		1	1.8	3.0	1.5	12.9	235	204
		2	3.0	5.0	3.5	20.7	233	186
18047	0.201	0.5	1.0	1.5	0	3.8	218	210
		1	1.5	2.5	0.5	4.9	215	205
		2	3.0	3.0	1	7.3	220	204
58003	0.155	0.5	1.6	1.6	0	2	235	230
		1	2.1	3.8	0.5	8	235	212
		2	3	5.4	1	15	235	195

Although Pcm appears to provide a reasonable indicator of HAZ softening susceptibility, the results do exhibit scatter. This indicates that, in addition to Pcm, there may be other factors that influence HAZ softening (e.g., TMCP processing parameters – particularly water-cooling rate, pipe forming strains, and strain aging). In addition, Pcm may not be the best parameter to characterize HAZ softening because it was originally developed as a parameter to measure hardenability.

In terms of controlling HAZ softening, it seems logical that pipe materials that represent the highest potential for HAZ softening are lean alloy (low Pcm) steels, where the steel derives a large percentage of its strength from aggressive water cooling during TMCP processing. On-line accelerated cooling (OLAC) has been adopted by a number of steel producers as a method of achieving mechanical properties (strength) from lean alloy designs with reduced alloy costs. Steel producers consider TMCP parameters highly confidential (business sensitive) and, consequently, manufacturing procedure specifications (MPSs) deliberately provide wide ranges of TMCP processing parameters.

In summary, although the BOP test results indicate that HAZ softening susceptibility increases as Pcm decreases, the steels tested did not cover the entire range of Grade X70 alloy designs and, in particular, did not include steels with low carbon but medium Pcm (i.e., low carbon steels with significant alloy additions to promote strength). In addition, the results may have been influenced by the WT variation of the BOP samples. For these reasons, although the HAZ softening results exhibit clear trends, no firm recommendations can be made on steel composition limits to mitigate HAZ softening without additional testing. Nevertheless, although the BOP test results did not permit the development of firm recommendations about steel chemical composition, they did indicate that HAZ softening susceptibility increases as Pcm decreases. As a result, specifying a minimum Pcm (e.g., a Pcm >0.14) may also help mitigate HAZ softening.

The X70 Database developed in Phase 2 of the JIP included the steel compositions for the pipe as well as tensile and hardness properties. Cumulative probability plots, which represent current manufacturing practices, are presented in Figure 17 and Figure 18 for Carbon (%) and Pcm. Each figure contains plots for SAWL, SAWH and HF-ERW pipe. It is evident from Figure 17 and Figure 18 that the following percentages of pipe had Pcm values greater than or equal to 0.12 and 0.14:

- Pcm ≥ 0.14
  - SAWL Pipe : >99%
  - SAWH Pipe : 80%
  - HF-ERW Pipe : 50%
- Pcm ≥ 0.12
  - SAWL Pipe : 100%
  - SAWH Pipe : 95%
  - HF-ERW Pipe : >99%%

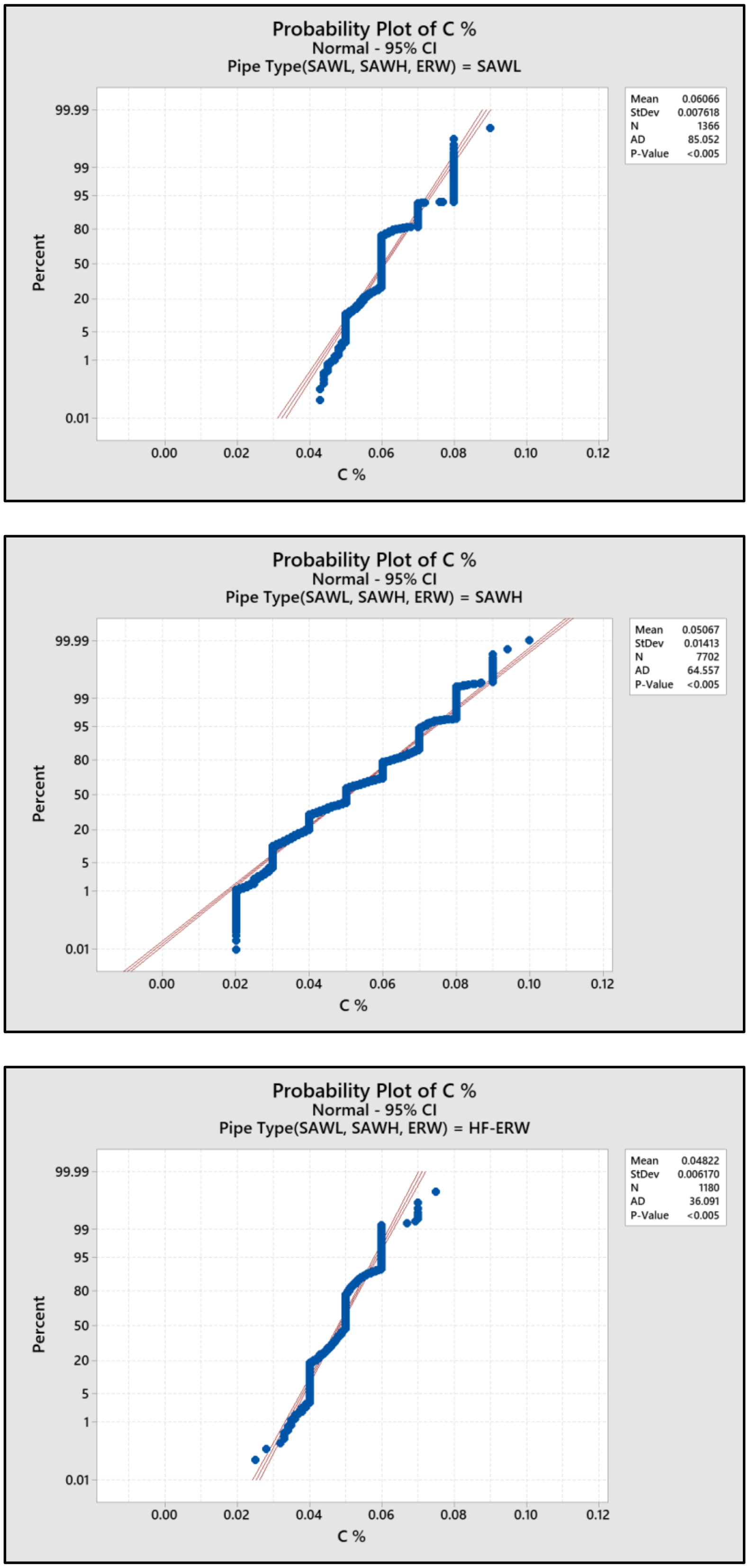


Figure 17. Cumulative Probability Distribution Plots of Carbon (%)

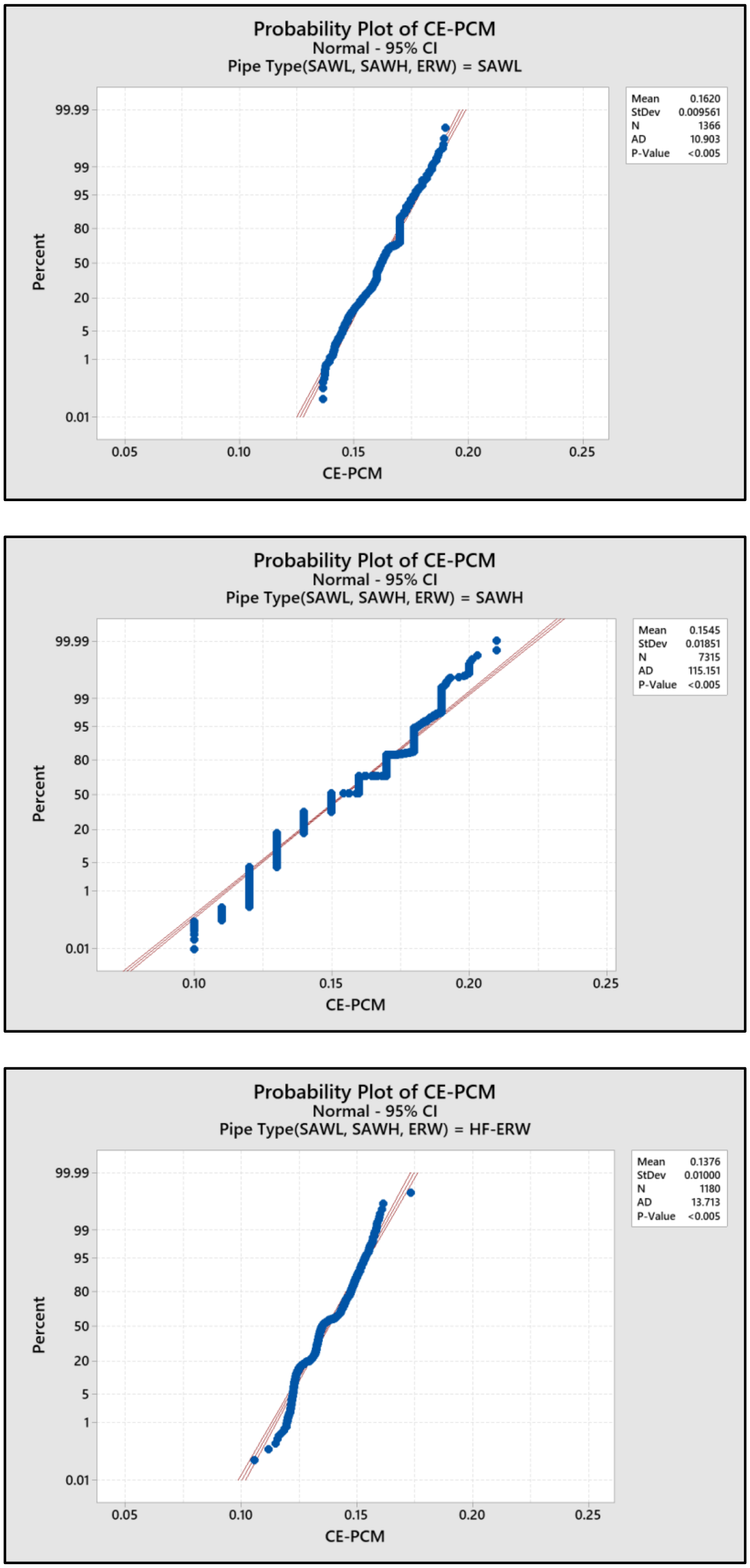


Figure 18. Cumulative Probability Distribution Plots of Pcm

The results of the JIP BOP tests and the conclusion that HAZ softening is more pronounced in low carbon, lean alloyed (low Pcm) steels is consistent with a previous PRCI study [22] in which it was concluded:

- Low carbon lean alloyed (low Pcm) steels with Y/T ratios above 0.90 are particularly susceptible to HAZ softening.
- The reduction in yield strength in the softened HAZ is much more pronounced than the reduction in hardness.
- The more pronounced reduction in HAZ yield strength (compared to hardness) is particularly important with respect to the structural significance of HAZ softening.

8.5 Girth Weld Test Program: HAZ Hardness Tests

In addition to the BOP Test Program, the girth weld test program presented in Chapter 7 also included hardness testing. A macro sample was extracted from each girth weld sample for detailed hardness mapping. The hardness testing was performed using an automated hardness testing machine with a 5 kg load. The indent spacing in the horizontal and vertical directions was 0.50 mm.

The results of the hardness tests were analyzed by selecting hardness traverses at the ¼, ½ and ¾ through thickness locations measured from the OD surface. Table 24 summarizes the results of the hardness traverses and contains the following information for each hardness scan – plus the averages of all three scans (which are highlighted in red in Table 24):

- Average pipe hardness (average pipe hardness results at the end of the traverses);
- Average weld hardness;
- Minimum HAZ hardness;
- HAZ softening (Min. HAZ Hardness vs. Average Pipe Hardness);
- Width of softened HAZ (width of HAZ where hardness < average parent pipe);
- Width of softened HAZ divided by pipe WT.

The average hardness results for each girth weld sample are presented in Figure 19 as a plot of HAZ Softening (%) vs. Carbon (%) and Pcm. It is evident that the results exhibit significant scatter with no discernable trend between HAZ softening and Carbon (%) or Pcm. Since the girth weld samples contained a range of pipe diameters, WTs, and were made with different SMAW weld procedures, which would have included a range of heat inputs, this conclusion is not surprising.

Figure 19 presents plots of minimum HAZ hardness vs. Carbon (%) and Pcm. Again, the results exhibit significant scatter with no discernable trend.

Figure 21 presents the results of the hardness results as plots of the HAZ softened width vs. pipe WT. The upper plot presents a plot of the average HAZ width vs the pipe wall thickness. The lower plot shows the same results but with the HAZ width normalized by the pipe wall thickness. The results show, as expected, that as the pipe WT increases (increasing heat sink) the width of the softened HAZ decreases. However, it should be noted that the two results for the largest pipe wall thicknesses were shop fabricated welds as opposed to field welds. These welds, which were made at CRC, were welded with a Heat Input in the range 1.2 – 1.5 kJ/mm which may be significantly lower than the other welds which were made in the field and donated by JIP sponsors. Based on the results from the upper plot in Figure 20 the HAZ width for pipe with wall thicknesses up to 16 mm (i.e., all the field girth welds) appear to relatively independent of pipe WT. However, when the HAZ width is normalized by pipe wall thickness (lower plot in Figure 22) a clear trend emerges. The data in the lower plot of Figure 20 indicates that the softened HAZ width exceeds 25% of the pipe WT for pipe WTs less than 15 mm.

Table 24. Results of Hardness Tests

Sample	Diameter (inch)	Wall Thickness (inch)	Location	Avg Pipe Hardness	Avg Weld Hardness	Min HAZ Hardness	HAZ Softening (%)	HAZ Soft Width (mm)	HAZ Soft Width (%WT)
101171	36	0.540	1/4	200	190	171	14.5%	4.0	29.2%
			1/2	210	180	175	16.7%	3.0	21.9%
			3/4	205	185	166	19.0%	5.0	36.5%
			Average	**205**	**185**	**171**	**16.7%**	**4.0**	**29.2%**
101223	36	0.438	1/4	225	200	185	17.8%	4.0	36.0%
			1/2	220	185	175	20.5%	5.0	44.9%
			3/4	220	180	175	20.5%	6.0	53.9%
			Average	222	188	178	19.5%	5.0	44.9%
101227	36	0.375	1/4	215	210	181	15.8%	3.0	31.5%
			1/2	210	210	178	15.2%	4.0	42.0%
			3/4	210	190	176	16.2%	6.0	63.0%
			Average	212	203	178	15.7%	4.3	45.5%
101228	42	0.510	1/4	220	195	185	15.9%	5.0	38.6%
			1/2	220	205	195	11.4%	4.0	30.9%
			3/4	220	190	186	15.5%	4.0	30.9%
			Average	220	197	189	14.2%	4.3	33.5%
101229	36	0.515	1/4	210	185	180	14.3%	3.0	22.9%
			1/2	205	200	182	11.2%	4.0	30.6%
			3/4	210	185	182	13.3%	4.0	30.6%
			Average	208	190	181	13.0%	3.7	28.0%
101231	30	0.625	1/4	225	205	195	13.3%	4.0	25.2%
			1/2	215	205	195	9.3%	2.0	12.6%
			3/4	225	200	196	12.9%	4.0	25.2%
			Average	222	203	195	11.9%	3.3	21.0%
101232	36	0.515	1/4	215	200	184	14.4%	4.0	30.6%
			1/2	205	190	180	12.2%	4.0	30.6%
			3/4	210	185	171	18.6%	5.0	38.2%
			Average	210	192	178	15.1%	4.3	33.1%
101276	30	0.476	1/4	220	205	185	15.9%	3.0	24.8%
			1/2	215	190	194	9.8%	3.0	24.8%
			3/4	220	195	195	11.4%	3.0	24.8%
			Average	218	197	191	12.4%	3.0	24.8%
101279	30	0.476	1/4	220	195	190	13.6%	3.0	24.8%
			1/2	210	185	187	11.0%	3.5	28.9%
			3/4	220	185	182	17.3%	3.0	24.8%
			Average	217	188	186	14.0%	3.2	26.2%
102658	30	0.375	1/4	200	185	170	15.0%	4.0	42.0%
			1/2	180	205	165	8.3%	4.0	42.0%
			3/4	190	200	170	10.5%	5.0	52.5%
			Average	190	197	168	11.4%	4.3	45.5%
102659	30	0.375	1/4	195	200	178	8.7%	3.0	31.5%
			1/2	195	210	180	7.7%	3.0	31.5%
			3/4	195	205	176	9.7%	4.0	42.0%
			Average	195	205	178	8.7%	3.3	35.0%
102706	24	0.375	1/4	215	205	187	13.0%	3.0	31.5%
			1/2	210	215	183	12.9%	4.0	42.0%
			3/4	220	212	176	20.0%	3.0	31.5%
			Average	215	211	182	15.3%	3.3	35.0%
102707	20	0.750	1/4	190	215	168	11.6%	2.0	10.5%
			1/2	190	205	165	13.2%	3.0	15.7%
			3/4	190	190	156	17.9%	3.0	15.7%
			Average	190	203	163	14.2%	2.7	14.0%
104629	48	0.688	1/4	230	195	192	16.5%	2.5	14.3%
			1/2	225	185	192	14.7%	2.5	14.3%
			3/4	225	190	182	19.1%	2.5	14.3%
			Average	227	190	189	16.8%	2.5	14.3%
107263	36	0.476	1/4	220	205	186	15.5%	6.0	49.6%
			1/2	215	205	180	16.3%	5.0	41.4%
			3/4	220	195	185	15.9%	5.0	41.4%
			Average	218	202	184	15.9%	5.3	44.1%

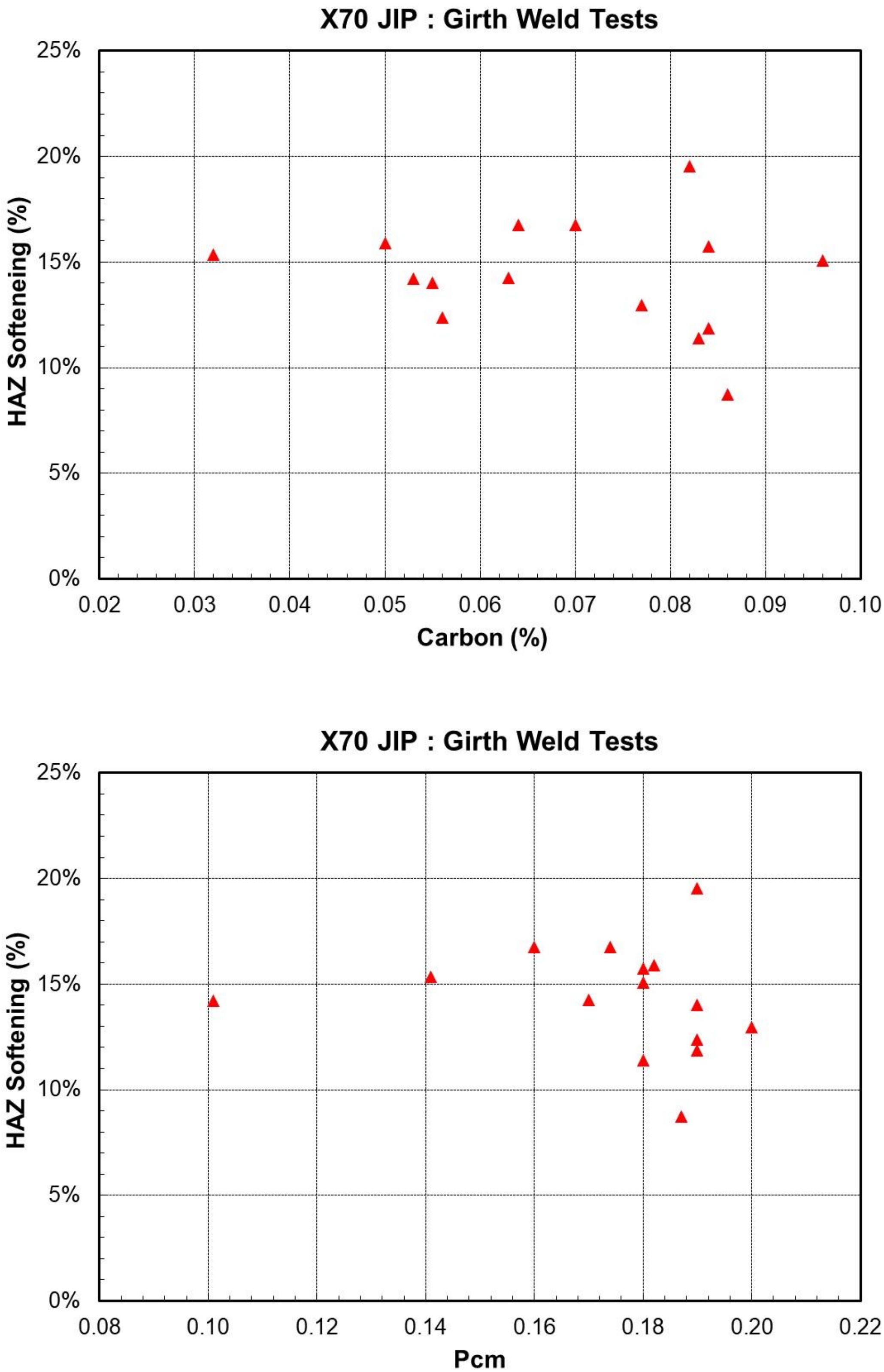
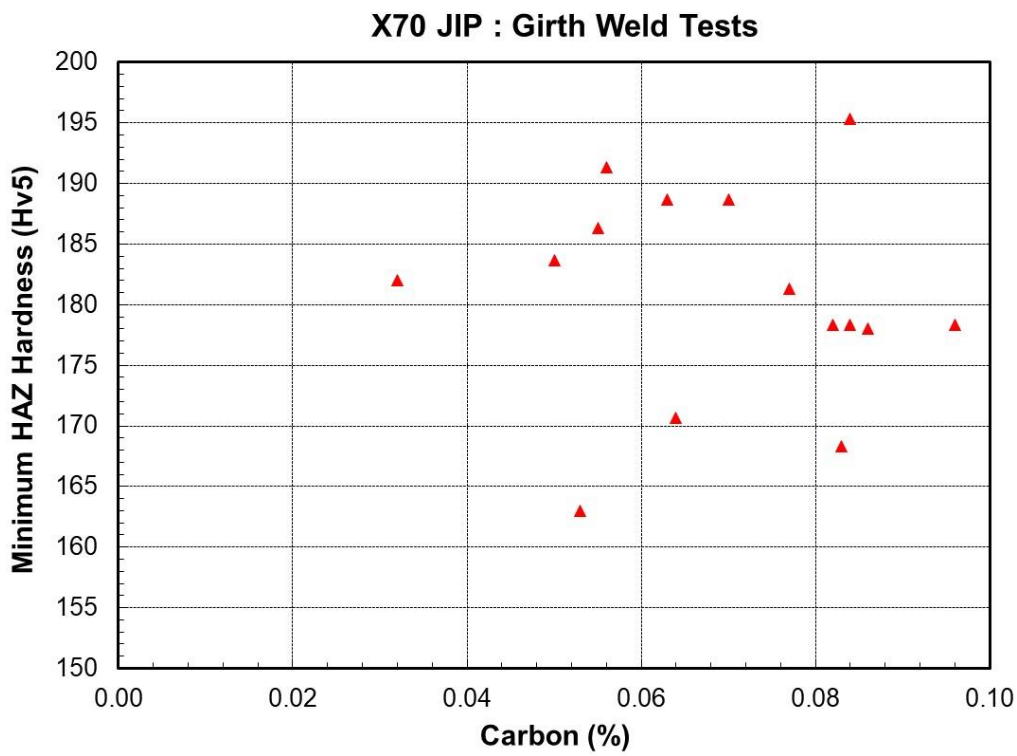


Figure 19. Average HAZ Softening (%) as a Function of Carbon (%) and Pcm



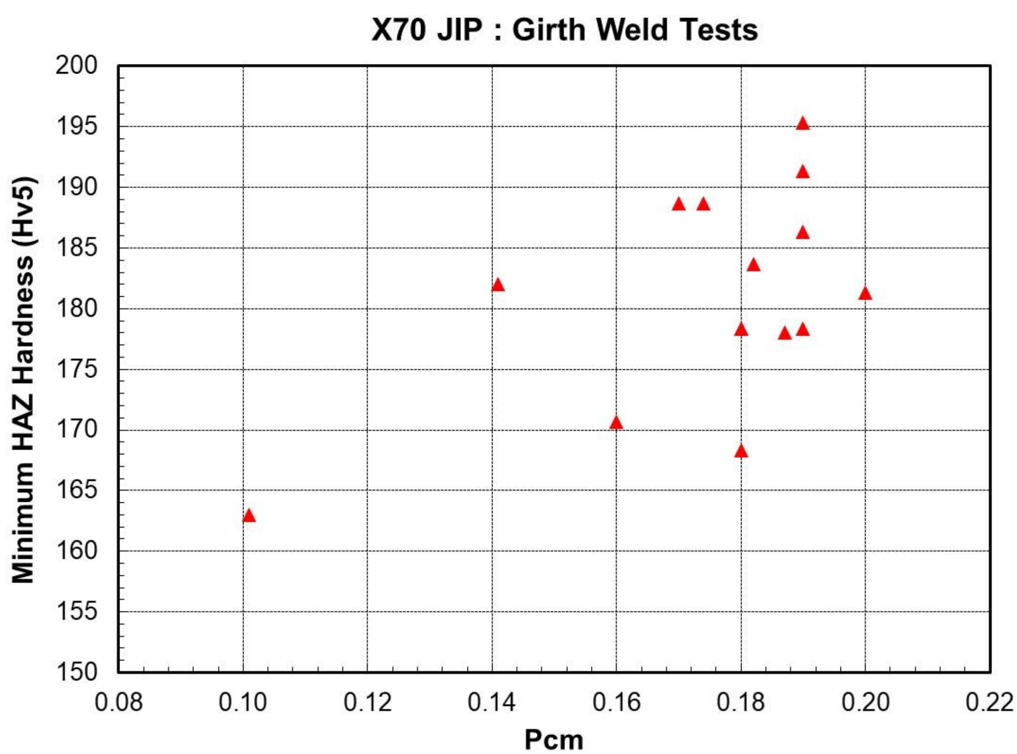
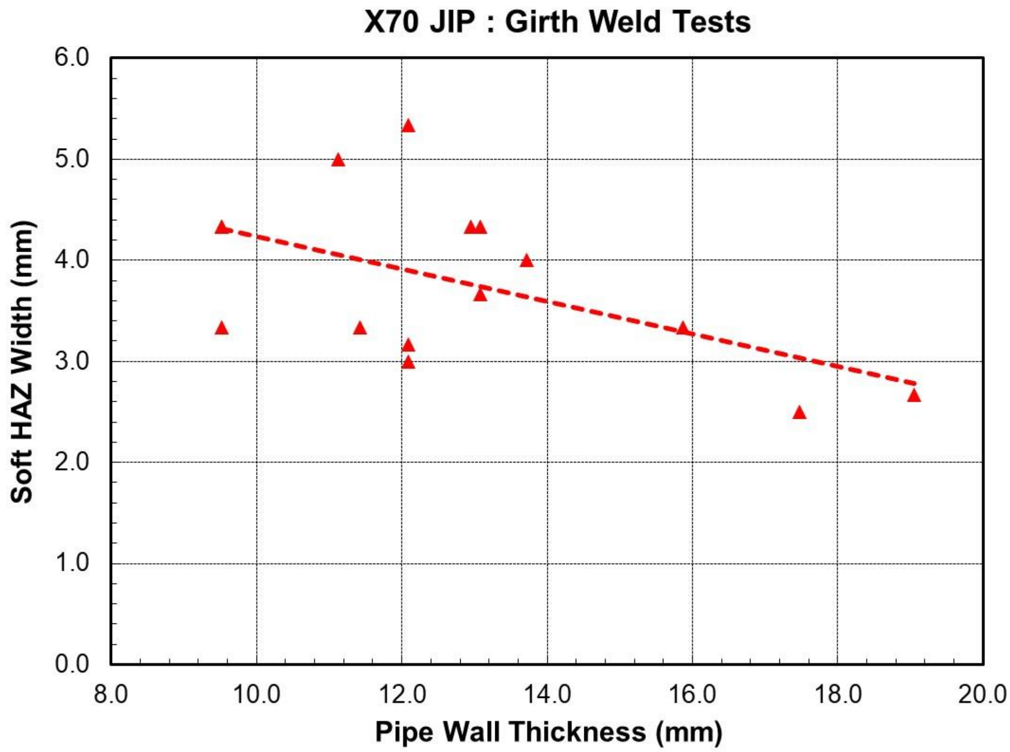


Figure 20. Minimum HAZ Hardness as a Function of Carbon (%) and Pcm



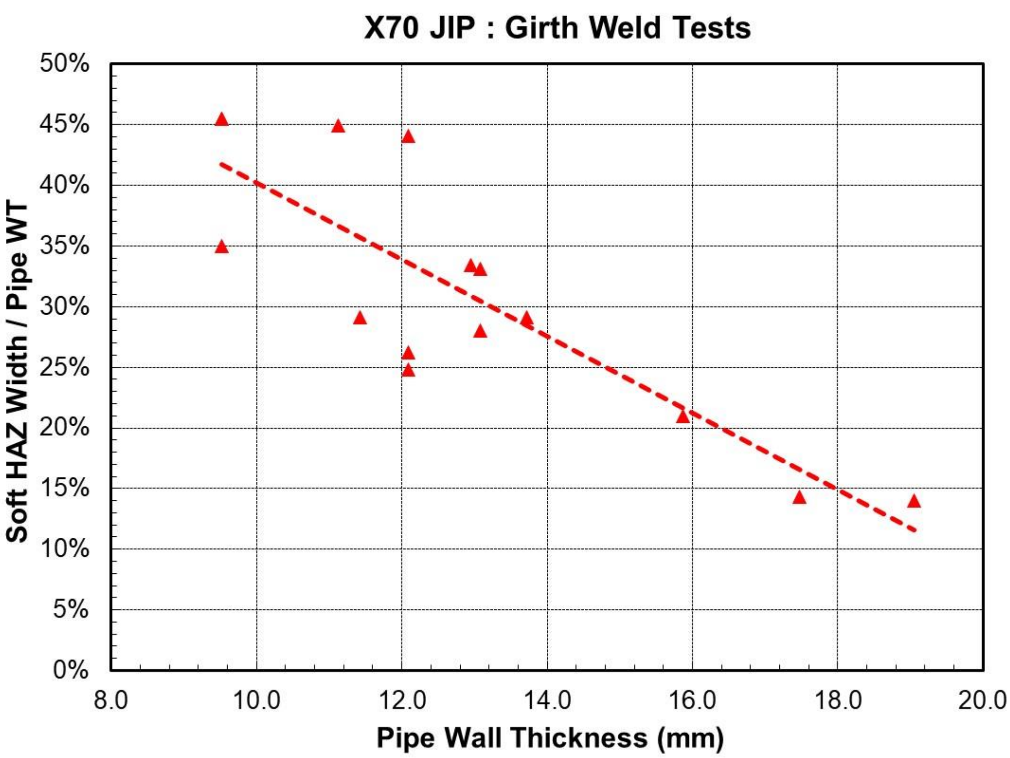


Figure 21. Width of Softened HAZ Softened Zone vs. Pipe Wall Thickness

The girth weld test results confirm that the average HAZ softening in the girth welds ranged from 8.7% to 19.5% and that the widths of the softened HAZ region ranged from 2.5 to 5.0 mm or 14% to 45% of the pipe WT. The highest level of HAZ softening was exhibited by Girth Weld 101223 (36" x 0.438") which produced 19.5% HAZ softening with a softened HAZ width equal to 45% of the pipe WT. All four of the CWT tests for this girth weld failed in the HAZ (Weld Cap and Root in place) or through the weld (Weld Cap and Root machined off).

Table 25 summarizes the level of HAZ softening and the width of the softened HAZ in girth welds that failed with average pipe strains of less than 1.0% when the weld cap and weld root were removed. Table 25 also contains the calculated girth weld under-match (based on YS), which was determined from the AWT tensile test results.

Table 25. Width of Softened HAZ in Girth Welds that Failed at <1.0% Pipe Strain

Girth Weld	Pipe Size (in.)	HAZ Softening (%)	Width of Softened HAZ (mm)	Width of Softened HAZ (% WT)	Girth Weld YS Under-match (%)
101223	36 x 0.438	19.5	5.0	44.9	30.2
101276	30 x 0.476	12.4	3.0	24.8	24.2
101279	30 x 0.476	14.0	3.2	26.2	18.2
102706	24 x 0.375	15.3	3.3	34.6	8.0
104629	48 x 0.688	16.8	2.5	14.3	16.4

Of the girth welds listed in Table 25 the only girth weld failure that clearly occurred through the pipe HAZ was Girth Weld 104629 (48 in. x 0.688 in.), which had the smallest softened HAZ width of all the girth welds listed in Table 25. The CWT tests on this girth weld (2 tests with weld root and weld root intact and 2 tests with weld cap and weld root machined off) all failed in the HAZ at pipe strains less than 0.5%. The measured AWT properties for Girth Weld 104629 were:

- YS = 70.0 ksi
- TS = 83.4 ksi

These AWT properties are typical of those reported in Table 14 of this report which summarizes the AWT properties of the other girth weld samples. In comparison the pipe material Yield Strength in the longitudinal direction (YS-L) was around 90 ksi.

The CWT specimens were instrumented with multiple extensometers to enable strains to be measured at the following locations:

- Pipe A
- Pipe B
- Weld region (1" Gauge length)
- Weld region + HAZ + Pipe (2" Gauge length)

The main difference in the stress strain curves for the weld region is that the 1" gauge length covers the weld cap but the 2" gauge length covers the weld cap and the HAZ region either side of the girth weld. One of the stress-strain plots for Girth Weld 104629 (weld cap and weld root machined off) is presented in Figure 22. The difference between the 1" and 2" gauge length strain results is very significant highlighting strain concentration in the pipe HAZ. The stress-strain plots also confirm that failure occurred before the pipe exhibited any significant yielding, i.e., the girth weld was significantly under-matched. As stated previously if a girth weld is significantly under-matched then the presence of HAZ softening will make an already bad situation even worse and in the case of Girth Weld 104629 resulted in failures through the HAZ.

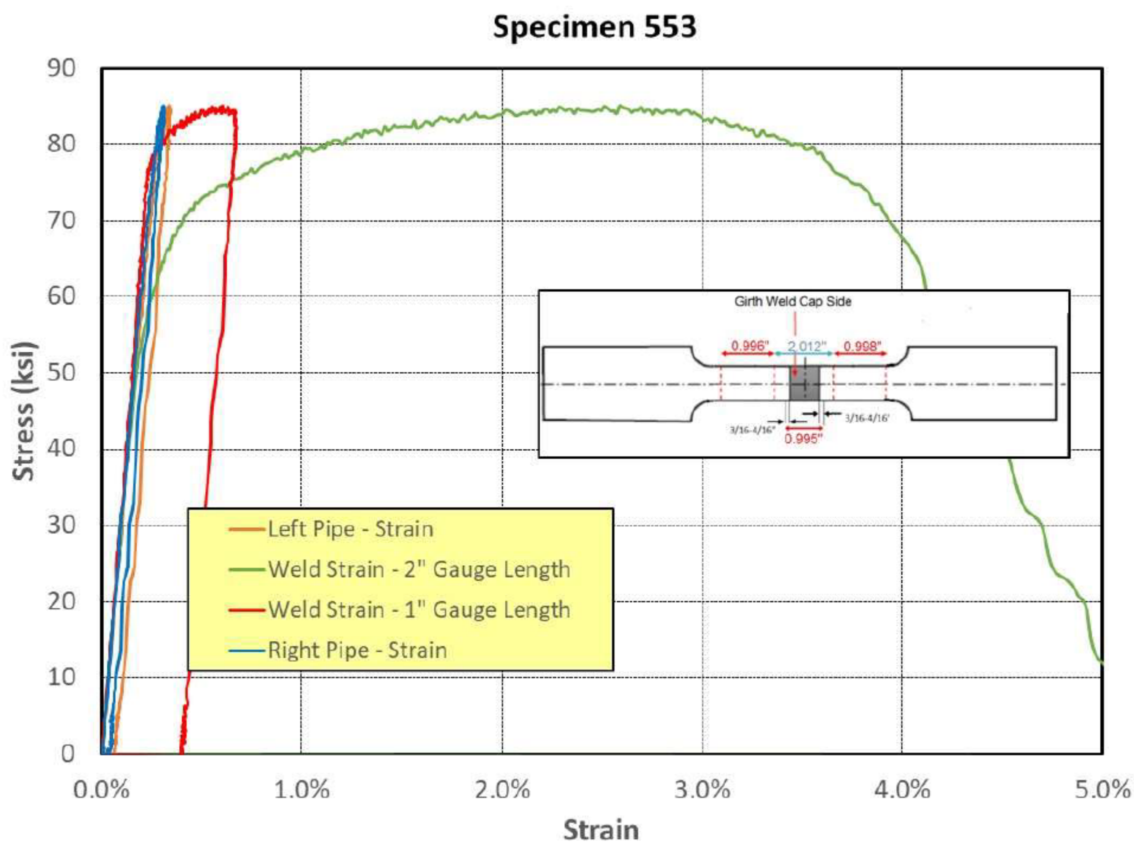


Figure 22. Stress-Strain Plots for Girth Weld 104629 (48" x 0.689")

Although the CWT results clearly illustrate that yielding generally starts in the HAZ region, the final failure location is a stronger function of weld metal under-match. In cases where under-match is present, HAZ softening can result in additional strain accumulation in the weld/HAZ zone and result in low strain failures.

8.6 Recommendations

It was originally hoped that the results from the BOP tests and hardness results from the girth weld tests would enable guidelines to be developed to mitigate HAZ softening in Grade X70 pipe.

Although the BOP test results indicate that HAZ softening susceptibility increases as Pcm decreases, the steels tested do not cover the entire range of Grade X70 alloy designs and, in particular, do not include steels that are low carbon and medium Pcm (i.e., low carbon steels with significant alloy additions to promote strength). In addition, the BOP results may have been influenced by the WT variation of the BOP samples. The hardness results from the girth weld tests also exhibit significant scatter, with no obvious trends. Thus, although the BOP HAZ softening results exhibit clear trends, no firm recommendations can be made on steel composition limits to mitigate HAZ softening without additional testing. Nevertheless, it seems logical that the pipe materials that represent the highest potential to HAZ softening are lean alloy (low Pcm) steels, where the steel derives a large percentage of its strength from aggressive water cooling during TMCP processing.

The degree of HAZ softening and the width of the softened HAZ are very dependent on weld heat input, so limits should be placed on the maximum heat input. A maximum heat input of 1.0 - 1.5 kJ/mm is proposed for SMAW and SMAW/FCAW girth welds. In addition, although the BOP test results did not permit the development of firm recommendations about steel chemical composition, they did indicate that HAZ softening susceptibility increases as Pcm decreases. As a result, specifying a minimum Pcm (e.g., a Pcm >0.14) may also help mitigate HAZ softening. Based on the BOP test results this will assist in keeping HAZ softening to less than 20%.

9 Pipe Tensile Properties vs. Under/Over-match vs. HAZ Softening

9.1 General

Phase 2 of the JIP included a task that involved detailed Finite Element Analysis (FEA) to investigate how the tensile strain capacity (TSC) of girth welds is influenced by:

- Weld strength mismatch;
- HAZ softening; and,
- Weld profile.

The FEA matrix included analysis of girth welds with regular weld caps and enhanced (large) weld caps. Analyses were performed for the following pipe sizes:

- 24 in. OD x 3/8 in. WT; and,
- 30 in. OD x 5/8 in. WT.

Figure 23 presents a schematic of the FEA models for the two pipe sizes (regular weld caps). Since all low strain girth weld failures occurred in SMAW or SMAW/FCAW girth welds, the models focused on a weld geometry with a 30° bevel.

The FEA models were developed to enable different material properties (tensile properties) to be assigned to the pipe material, weld metal, and HAZ. The HAZ tensile properties were modeled using a hyperbolic tangent function to reflect the variation of hardness across the HAZ. Figure 24 presents a schematic distribution of the HAZ strength distribution. This distribution is a simplification of the typical HAZ strength distribution presented in Figure 8, i.e., it does not include regions of increased HAZ hardness due to transformation and precipitation hardening. Nevertheless, since the key elements of a softened HAZ with respect to structural behavior are the degree of HAZ softening (%) and the width of the softened HAZ the method of modelling the HAZ is considered appropriate.

The FEA matrix covered these cases:

- Two pipe sizes: 24 in. OD x 3/8 in. WT and 30 in. OD x 5/8 in. WT;
- Three pipe strengths: TS = 85, 94, and 106 ksi;
- Three Y/T ratios for each pipe strength: low, medium and high;
- Two levels of HAZ softening: 10% and 20%;
- Two HAZ widths: 2.5 mm and 5.0 mm;
- Weld roots: E6010 and E8010;
- Weld fill-and-cap passes (E8010); and,
- Hi-lo misalignment: 1/16 in.

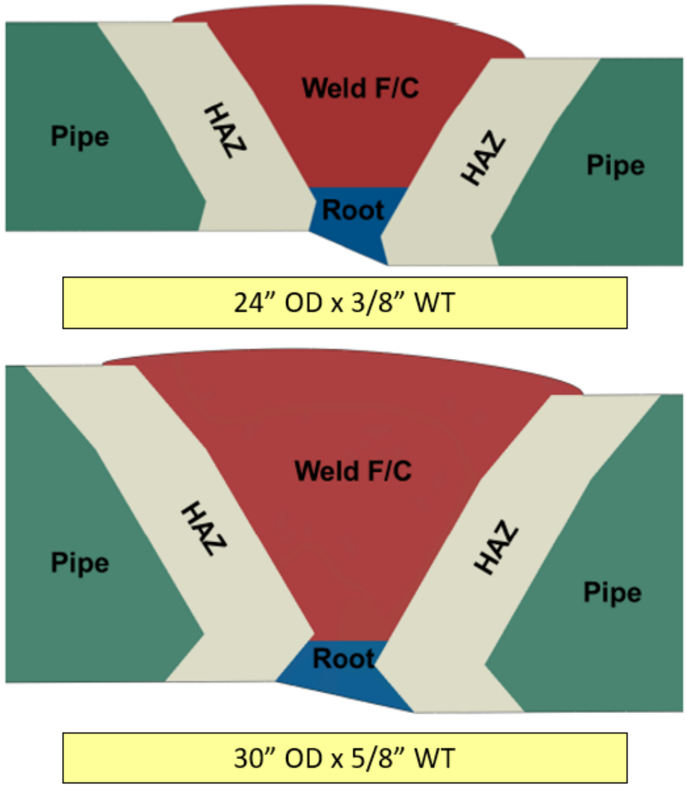


Figure 23. Schematic of FEA Models (Regular Weld Cap)

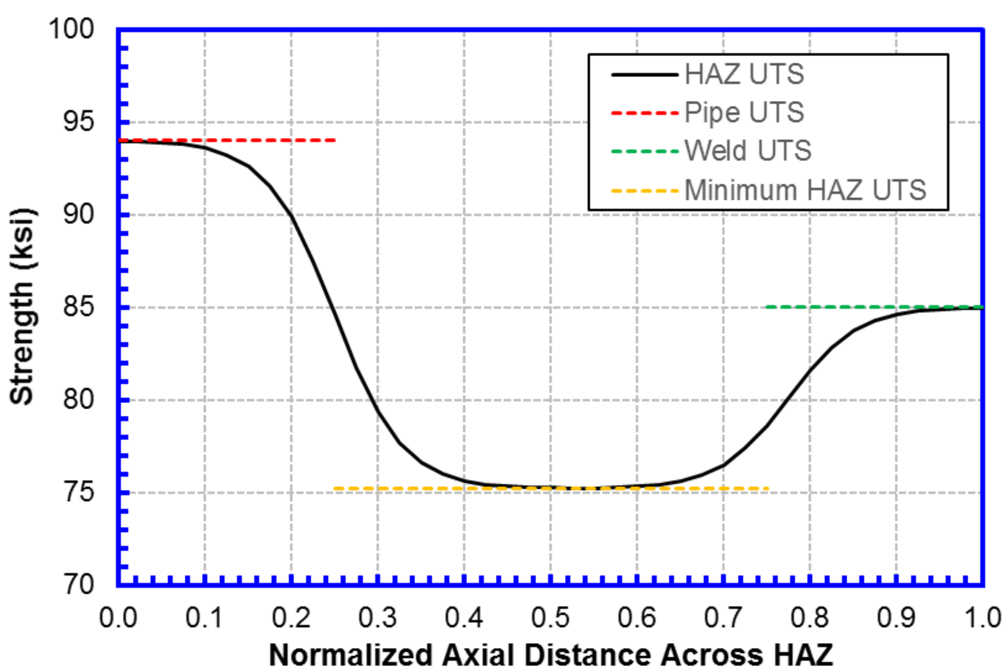


Figure 24. Schematic of HAZ Strength

The evolution of strain in an under-matched girth weld is illustrated in Figure 25.

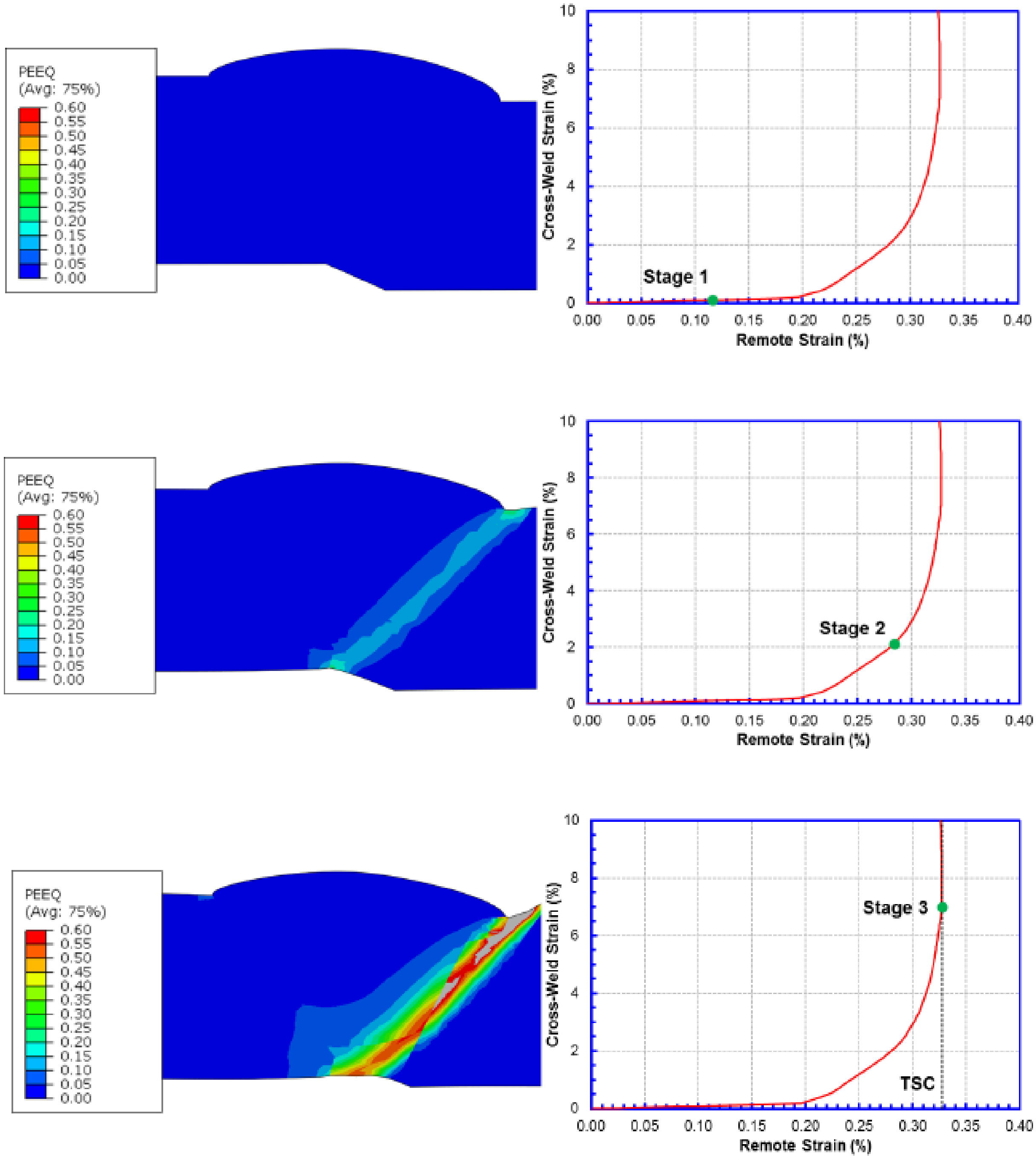


Figure 25. Development of Strain in an Under-matched Girth Weld

The strain development can be characterized in three stages:

1. Stage 1

   The cross-weld strain is comparable to the remote strain, and no strain localization is present in the girth weld region.

2. Stage 2

   Strain localization occurs along a band with low material strength and shortest path for plastic shearing. In this case, the shear band links the weld toes between the ID and OD.

3. Stage 3

   Strain localization becomes unbounded with increasing load. Any further deformation of the pipe segment containing the girth weld is accommodated by the deformation associated with the shear band.

For welds with regular caps, the FEA results confirmed that the following factors, in order of importance, control the TSC of girth welds:

1. Weld strength under-match;
2. HAZ softening (level and width of softening); and,
3. Weld root strength.

Weld strength mismatch, in general, plays a more dominant role than HAZ softening. However, lower-impact parameters can play a more prominent role if the higher-order parameters do not dominate. For instance, if the weld strength under-matching is not excessive, HAZ softening can have a meaningful impact on TSC. However, if the weld strength under-matching level is high, the TSC would be low – regardless the level of HAZ softening.

Enhanced weld caps are effective in increasing the TSC of girth welds. Increasing the width of the weld cap is more important than increasing the cap height in most cases. However, having a large cap height is beneficial if the weld strength under-matching level is high.

Table 26 presents selected FEA results for cases where the tensile strength of the weld (cap and fill passes) equals the tensile strength of the pipe. Table 26 includes results for three levels of yield strength matching:

- 10% under-match;
- matching; and,
- 10% over-matching.

Table 26 also includes results for two weld root strengths (E6010 and E8010). Red cells identify cases where the TSC is <1.0%. The results confirm that low TSC results are produced when:

- The weld metal YS under-matches parent pipe YS;
- The weld root is low strength (E6010); and,
- There is high HAZ softening (20%).

Table 26. TSC Results for Cases where Fill and Cap Passes Match Parent Pipe TS

Diameter (inch)	Wall (inch)	HAZ Width (mm)	HAZ Soft (%)	Root Pass	TS Match	YS Match	TSC (%)	TSC Pass	Fill / Cap Pass Matching
24	0.375	2.5	10%	E6010	1	1.10	> 2	Y	YS 10% Overmatch
				E8010	1	1.10	> 2	Y	
				E6010	1	1.00	1.75	Y	YS Matching
				E8010	1	1.00	> 2	Y	
				E6010	1	0.91	0.33	N	YS 10% Undermatch
				E8010	1	0.91	0.41	N	
24	0.375	2.5	20%	E6010	1	1.10	1.39	Y	YS 10% Overmatch
				E8010	1	1.10	1.59	Y	
				E6010	1	1.00	0.63	N	YS Matching
				E8010	1	1.00	0.73	N	
				E6010	1	0.91	0.24	N	YS 10% Undermatch
				E8010	1	0.91	0.25	N	
24	0.375	4.5	10%	E6010	1	1.10	> 2	Y	YS 10% Overmatch
				E8010	1	1.10	> 2	Y	
				E6010	1	1.00	1.15	Y	YS Matching
				E8010	1	1.00	1.48	Y	
				E6010	1	0.91	0.26	N	YS 10% Undermatch
				E8010	1	0.91	0.28	N	
24	0.375	4.5	20%	E6010	1	1.10	0.84	Y	YS 10% Overmatch
				E8010	1	1.10	0.85	Y	
				E6010	1	1.00	0.38	N	YS Matching
				E8010	1	1.00	0.42	N	
				E6010	1	0.91	0.2	N	YS 10% Undermatch
				E8010	1	0.91	0.21	N	
30	0.625	2.5	10%	E6010	1	1.10	> 2	Y	YS 10% Overmatch
				E8010	1	1.10	> 2	Y	
				E6010	1	1.00	> 2	Y	YS Matching
				E8010	1	1.00	> 2	Y	
				E6010	1	0.91	0.62	N	YS 10% Undermatch
				E8010	1	0.91	1.31	Y	
30	0.625	2.5	20%	E6010	1	1.10	> 2	Y	YS 10% Overmatch
				E8010	1	1.10	> 2	Y	
				E6010	1	1.00	1.24	Y	YS Matching
				E8010	1	1.00	1.48	Y	
				E6010	1	0.91	0.27	N	YS 10% Undermatch
				E8010	1	0.91	0.29	N	
30	0.625	4.5	10%	E6010	1	1.10	> 2	Y	YS 10% Overmatch
				E8010	1	1.10	> 2	Y	
				E6010	1	1.00	> 2	Y	YS Matching
				E8010	1	1.00	> 2	Y	
				E6010	1	0.91	0.33	N	YS 10% Undermatch
				E8010	1	0.91	0.52	N	
30	0.625	4.5	20%	E6010	1	1.10	1.52	Y	YS 10% Overmatch
				E8010	1	1.10	1.72	Y	
				E6010	1	1.00	0.64	N	YS Matching
				E8010	1	1.00	0.84	N	
				E6010	1	0.91	0.25	N	YS 10% Undermatch
				E8010	1	0.91	0.24	N	

Table 26 presents the TSC results for cases where the parent pipe and weld metal (Root and fill & cap passes) have matching properties (YS and TS) – i.e., the only region that has different properties is the HAZ. Table 27 confirms that, even if the weld matches the parent pipe, HAZ softening, by itself, can trigger low strain girth weld failures in cases where the HAZ softening is high (20%) and the HAZ width is >25% of the pipe WT. It should be noted that many of the girth welds tested in the JIP exhibited HAZ softening in the range 15 – 20% with 12 of the 15 girth welds exhibiting HAZ softened zones that exceeded 25% of the pipe WT.HAZ widths

Table 27. TSC Results for Cases where Entire Weld Matches Parent Pipe TS

Diameter (in.)	Wall (in.)	HAZ Width (mm)	HAZ Soft (%)	HAZ Width/Pipe WT (%)	TSC (%)	TSC >1%
24	0.375	2.5	10	26	>2	Y
24	0.375	2.5	20	26	0.73	N
24	0.375	4.5	10	47	1.48	Y
24	0.375	4.5	20	47	0.42	N
30	0.625	2.5	10	16	>2	Y
30	0.625	2.5	20	16	1.48	Y
30	0.625	4.5	10	28	>2	Y
30	0.625	4.5	20	28	0.84	N

9.2 Recommendations

The overall strategy to mitigate low strain girth weld failures in Grade X70 pipelines comprises three components:

1. Control pipe longitudinal tensile properties to facilitate girth weld over-match;
2. Adopt improved welding procedures to produce girth weld over-match; and,
3. Control/limit HAZ softening.

The results from the girth weld tests and TSC analyses confirm that the first and second components of the mitigation strategy (girth weld over-matching) are more important than HAZ softening. Indeed, the TSC results indicate that if the girth weld over-matches the parent pipe then a reasonable level of HAZ softening can be accommodated without the risk of low strain failures.

The TSC results indicate that low strain girth weld failures are more likely in these cases:

1. Under-matched girth welds;
2. Girth welds in thin wall pipe, particularly if the weld root is deposited with a lower strength consumable; and,
3. Girth welds with HAZ softening >20% and HAZ widths >25% of the pipe WT.

10 Alternative Manual Welding Options for X70 Pipelines

10.1 General

There may be situations where all-cellulosic SMAW welding procedures provide benefit including welding small replacement sections of pipeline, girth welds that have poor fit-up or pipe to fitting or pipe to forging girth welds. To evaluate alternative SMAW welding options Phase 2 of the JIP included a Task which explored alternative SMAW girth welding options.

10.2 Alternative SMAW Welding Trials

The objective of this task was to evaluate alternative welding options for girth welds made manually in X70 pipelines to the standard use of SMAW with cellulosic-coated electrodes.

The scope of this task is outlined below:

- Perform a desktop study to evaluate alternative manual welding options for X70 pipelines;
- Review the results of welding trials performed by Welding Contractors / Operators to assess alternative manual welding procedure options for X70 pipelines. Including:
    - E8010 SMAW for the Root pass;
    - Cellulosic-coated electrodes in conjunction with a wide, tall cap pass; and,
    - LHVD (e.g., E9045) SMAW for Fill & Cap passes.
- Compare and rank alternative manual weld procedure options in terms of:
    - Benefits and drawbacks;
    - Operability;
    - Productivity;
    - Risk of welding defects (e.g., root profile, undercut etc.);
    - Risk of weld metal hydrogen cracking / preheat requirements;
    - Potential weld metal strength produced by the different options; and,
    - Potential impact of base metal dilution.

The project did not investigate the use of semi-automatic FCAW-G because of the significant potential for HAZ softening, since heat input when using semi-automatic FCAW can be quite high and widely variable. This can be controlled with mechanized FCAW-G.

The project also did not investigate the use of SMAW using E9010 electrodes because of the significant potential for hydrogen cracking in the weld metal that results from the combination of high strength weld metal and very high weld hydrogen levels.

Finally, the project did not investigate the use of SMAW and close control of heat input level to prevent softening in the HAZ. Even considering simple methods like the run-out ratio scheme, it was felt that close control of heat input level would be difficult to achieve in the field and would require a high level of third party inspection. In addition, there is no way to confirm that heat input limits were followed after the weld is completed. In contrast, the use of a wide, tall cap can be confirmed after the weld is completed.

10.3 SMAW Welds with Enhanced Weld Cap and Cap Width

In the SMAW welding trials on a Grade X70 pipe material, success was achieved in producing overmatching strength using both cellulosic electrodes in conjunction with a wide / tall cap pass, and using LHVD electrodes for fill and cap passes. The use of higher strength E8010 electrodes for root pass welding (as opposed to E6010 electrodes) was also shown to help achieve girth weld over-matching.

One of the procedure options that was evaluated in the JIP was an all-cellulosic welding procedure with an enhanced weld cap (height and width) to provide additional weld reinforcement to increase the strength of the girth weld. The 20th and 21st Editions of API 1104 include the following requirement on the weld cap:

> *At no point shall the crown surface fall below the outside surface of the pipe, nor should it be raised above the parent metal by more than 1/16 in. (1.6 mm).*

Although the crown of the weld cap is not permitted to fall below the outside surface of the pipe (mandatory requirement) the limit on maximum cap height is a recommendation (defined by the word "should" as opposed to "shall") and therefore is not a mandatory requirement. In the 22nd Edition of API 1104, which should be issued in early 2020, the limit on weld cap height will be replaced by a requirement that the weld cap height must be within the limit specified in the Weld Procedure Specification. This allows the use of wider and taller weld caps, as long as the limits on cap dimensions (height and width) are specified in the WPS.

Girth weld trials performed using E6010 / E8010 and E8010 / E8010 SMAW procedures with enhanced weld caps demonstrated that the use of enhanced weld caps can produce over-matched girth welds due to the presence of the additional weld reinforcement. The adoption of a wider /taller weld cap also reduces the potential of a 45-degree shear band forming (i.e., discourages cross-weld failure from the weld toe on the OD to the opposite weld toe on the ID by cross-weld shear). The use of a wider / taller weld cap can help achieve girth weld matching or over-matching in thin wall pipelines where the root pass can comprise a significant proportion of the weld thickness.

Although the use of LHVD or FCAW-G are the preferred options for new construction, all-cellulosic SMAW procedures with an enhanced weld cap can be considered as an alternative option in circumstances where cellulosic welding is preferred.

11 Summary and Recommendations

11.1 General

Over the last 10 years, a number of girth weld failures have occurred in Grade X70 cross-country pipelines constructed using modern TMCP steel. The failures occurred during hydrotesting or after the pipeline entered service. Several of the failures occurred shortly after the pipeline entered service. These failures occurred at nominal strain levels less than 0.5% (i.e., within the limits of conventional stress-based design).

A JIP was launched in March 2017 to determine the underlying cause of these failures and develop guidelines to mitigate low strain failures in new Grade X70 pipelines.

The JIP was performed in three major phases:

1. Phase 1

   Review of Pipeline Failures and Development of Preliminary Guidelines.

2. Phase 2

   Experimental Test Program and Supplementary Finite Element Analysis.

3. Phase 3

   Best Practice Guidelines and Performance Requirements.

This Draft Final Report presents the recommendations developed from the JIP to mitigate low strain failures at Grade X70 girth welds.

11.2 Girth Weld Failures

In Phase 1 of the JIP, six girth weld failures were reviewed. This comprised a review of failure analysis reports prepared by/for associated pipeline companies and, in some cases, independent failure analysis performed by CRES. The primary purpose of the failure analysis reports was to demonstrate code compliance, as opposed to performing a detailed failure analysis. As a result, several of the failure analysis reports did not include extensive pipe and girth weld testing to fully characterize the pipe material and girth weld properties.

Four of the six girth weld failures were in-service failures. Two were hydrostatic test failures. Four of the six failures occurred on Grade X70 pipelines. One failure occurred on a Grade X52 pipeline. The remaining failure occurred at a Grade X70 to X80 transition weld with different pipe WTs on either side of the weld.

All the girth weld failures occurred in manual welds in SAWH or ERW pipe:

- Three failures (incidents 1, 5, and 6) occurred at pipe to pipe girth welds due to girth weld under-matching, in some cases, this was exacerbated by HAZ softening;
- One failure (Incident 2) occurred at an under-matched transition girth weld in which the heavier wall pipe was tapered at the pipe end, i.e., it was not counter-bored. The transition girth weld geometry will have produced a large SCF at the transition girth weld and further increased the strain in the under-matched girth weld and softened HAZ;
- One failure (Incident 3) occurred in an under-matched girth weld, which contained a small thumbnail flaw. This failure occurred through the pipe body / HAZ. The reason for this failure is not fully understood and will be further evaluated. Note the small thumbnail flaw (1.5 x 10 mm) is below the normal workmanship criteria in API 1104 and consequently this girth weld was compliant with API 1104; and,
- One failure (Incident 4) occurred at an under-matched girth weld that contained a hydrogen crack at a repair weld.

Three of the six failures occurred in girth welds that were poorly designed (i.e., non-counter-bored transition girth welds) or girth welds that contained flaws.

The three failures that are most concerning are those where failure occurred in nominally sound X70 girth welds that were fabricated using:

- Pipe that was compliant with API 5L; and/or,
- Weld procedures that met the requirements of API 1104.

The main contributing factors to the three failures in nominally-sound girth welds were girth weld under-matching and HAZ softening, confirming that guidelines to mitigate low strain failures in girth welds should focus on these two factors.

All the girth weld failures occurred in girth welds that under-matched the surrounding pipe material. Detailed hardness mapping was performed in four of the six incidents (incidents 1, 2, 4 and 5) to characterize the hardness of the girth weld, HAZ, and parent pipe. There is no hardness data for Incident 6 since the girth weld experienced fire damage. The hardness results confirmed a girth weld under-match level of approximately 10% for the fill-and-cap passes and 12 – 24% for the weld root region HAZ softening of 16 – 28% was measured.

Based on the major findings from Phase 1 of the JIP, Phase 2 set out to develop data that would enable the development of guidelines to mitigate low strain girth weld failures. The guidelines have three components as highlighted in Figure 26:

1. Control pipe longitudinal tensile properties to facilitate girth weld over-matching;
2. Implement improved girth welding practices (processes and procedures) that produce over-matched girth welds. Further, include additional WPQ requirements to ensure over-matched girth welds; and,
3. Develop guardrails to minimize/control girth weld HAZ softening.

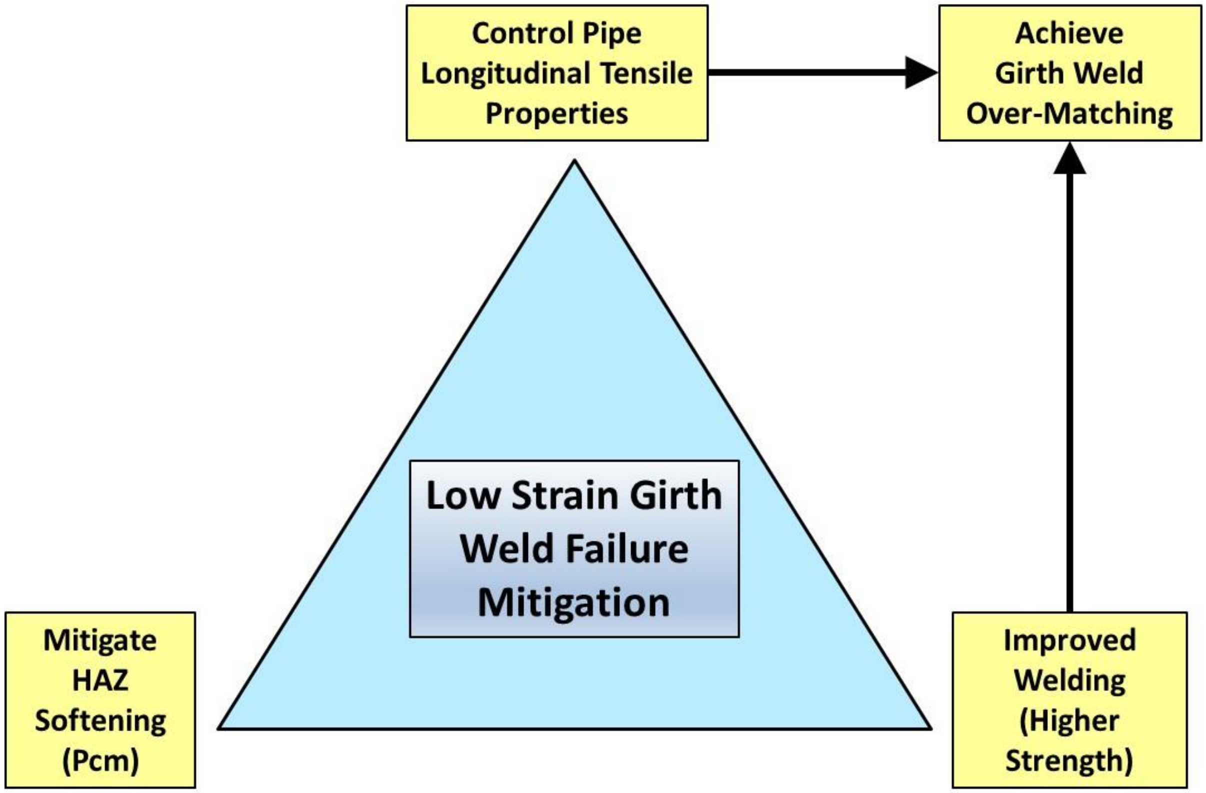


Figure 26. Low Strain Girth Weld Failure Mitigation Strategy

11.3 Guidelines to Mitigate Low Strain Girth Weld Failures

11.3.1 Pipe Tensile Properties

To facilitate girth weld over-matching in Grade X70 pipe, it is recommended that the following supplementary longitudinal tensile property requirements are specified for new pipe orders (SAWL, SAWH and HF-ERW):

1. Longitudinal tensile tests should be performed during MPQT and pipe production at the same frequency as transverse tensile tests to establish a full distribution of longitudinal tensile properties;
2. The longitudinal tensile tests should be performed on full thickness strap specimens; and,
3. The longitudinal tensile [properties should fall within the following ranges:
   - YS-L = SMYS to SMYS + 17 ksi (120 MPa);
   - TS-L = SMTS to SMTS + 17 ksi (120 MPa) and,
4. The re-test provisions for longitudinal tensile tests should be the same as transverse tensile Tests.

Although these requirements have been successfully applied in several recent major pipeline projects in which SAWH pipe was made at two different pipe mills, several steel producers and pipe mills have indicated that they will not be able to meet the 17 ksi cap requirement on YS-L and TS-L for SAWH and HF-ERW pipe. This in part is due to a) the current method of measuring transverse tensile properties in pipe using flattened strap specimens which tend to report lower values of yield strength due to the

Bauschinger effect and b) concerns regarding under strength pipe. Both of these factors have caused Pipe Mills to over-specify tensile properties in plate or coil to provide a margin that allows for a reduction in the transverse yield strength in pipe as measured using flattened strap specimens. Although transverse tensile properties in pipe are generally measured using flattened strap specimens there are other tensile specimen designs that could be adopted to address this issue, e.g., round bar specimens or ring expansion tests, both of which are permitted by API 5L.

In addition, it is recommended that during MPQT, longitudinal tensile tests are performed on pipe that has been aged at 250°C for one hour to determine the increase in YS-L and TS-L in the fully aged condition. The longitudinal tensile tests in the fully aged condition should be reported *For Information*. However, as more and more results are generated for longitudinal tensile properties in the fully aged condition, appropriate limits may be specified. The reason for specifying tensile properties in the fully aged condition is because they represent the properties that the pipe will exhibit during operation.

For pipe orders for short replacement sections, where pipe is likely to be procured from a pipe stock list as opposed to a new pipe order from a pipe mill, it is recommended that longitudinal tensile tests are performed to characterize the pipe longitudinal tensile properties. Pipe with extremely high longitudinal tensile properties should be avoided, e.g., pipe with longitudinal tensile properties that exceed the API 5L PSL2 limits for transverse tensile properties.

11.3.2 Girth Welding

To facilitate girth weld over-matching in X70 pipelines, the following recommendations are proposed for SMAW and SMAW/FCAW girth welds:

1. For new major Grade X70 pipeline projects girth weld procedures should be qualified on Project Pipe and ideally on pipe with longitudinal tensile properties that are at the upper range of the pipe order. In addition, consideration should be given to performing WPQ on pipe that has been subjected to an FBE thermal cycle to account for aging. If pre-existing weld procedures are used without re-qualification on project pipe, then girth weld over-matching must be ensured. This can be achieved by performing All Weld Tensile (AWT) tests to measure weld metal tensile properties to demonstrate that the measured weld metal tensile properties (YS and TS) exceed the maximum pipe longitudinal tensile properties after FBE coating;
2. CWT tests should be performed on specimens with the weld reinforcement in place;
3. CWT specimens should fail in the base pipe (i.e., failure in the girth weld or HAZ is not acceptable). In cases where CWT specimens fail in the weld region but after significant deformation occurs in the parent pipe (i.e., gross section yielding occurs in the parent pipe), the suitability of the weld procedure can be assessed on a case-by-case basis;
4. Mainline pipe-to-pipe, or tie-in girth welds should be made using SMAW LHVD (e.g., E9045 or E10045) or FCAW-G (e.g., E91 T1, E100 T1, etc.) consumables for the fill-and-cap passes. Although the weld root can be made using E6010 consumables, the use of E8010 for the weld root should be encouraged – particularly for thin wall pipe;
5. There are cases where the increased flexibility of an all-cellulosic SMAW girth weld provides clear benefits. However, the Project Technical Team recommends that SMAW procedures using E6010 (for the root/hot pass) and E8010 (for the fill-and-cap passes) should be limited to pipe assemblies and station piping.

6. Transition welds between pipes of the same grade but different wall thicknesses should be made using pipe that is counter-bored so that the pipe on either side of the girth weld is the same thickness. This will eliminate the SCF due to wall thickness difference wither side of the girth weld.
7. For transition welds between pipes of different grades and wall thickness, it is necessary to follow the guidance given in Appendix I of ASME B31.8 (or similar guidance given in B31.4) which calls for an internal taper between 14 and 30 degrees. If you simply counterbore the lower strength material, the thinner material on the lower strength side will be under-designed for hoop strength.
8. The degree of HAZ softening and the width of the softened HAZ are very dependent on weld heat input, so limits should be placed on the maximum heat input. A maximum heat input of 1.0 - 1.5 kJ/mm is proposed for SMAW and SMAW/FCAW girth welds. This is particularly important for thinner wall pipe where the HAZ may be a significant proportion of the pipe wall thickness. For heavier wall pipe an increased Heat Input may be used provided it is qualified. Monitoring electrode run-out length can be used to monitor SMAW heat input during construction.

11.3.3 HAZ Softening

It was originally hoped that the results from the Bead on Pipe and Girth Weld Test programs would enable development of guidelines to mitigate HAZ softening in Grade X70 pipe.

Although the BOP test results indicate that HAZ softening susceptibility increases as Pcm decreases, the steels tested do not cover the entire range of Grade X70 alloy designs. In particular they did not include low Carbon (%), medium to high Pcm steels (i.e., low Carbon steels with significant alloy additions to help promote strength). In addition, there is concern that the BOP results may have been influenced by the WT variation of the BOP samples. The hardness results from the girth weld tests also exhibit significant scatter, with no obvious trends. Thus, no firm recommendations can be made on steel composition limits to mitigate HAZ softening without additional testing. Nevertheless, it seems logical that the pipe materials that may represent the highest potential to HAZ softening are lean alloy (low Pcm) steels where the steel derives a large percentage of its strength from aggressive water cooling during the later stages of TMCP processing.

The degree of HAZ softening and the width of the softened HAZ are very dependent on weld heat input, so limits should be placed on the maximum heat input. A maximum heat input of 1.0 - 1.5 kJ/mm is proposed for SMAW and SMAW/FCAW girth welds.

In addition, although the BOP test results did not permit the development of firm recommendations about steel chemical composition, they did indicate that HAZ softening susceptibility increases as Pcm decreases. As a result, specifying a minimum Pcm (e.g., a Pcm >0.14) may also help mitigate HAZ softening.

11.4 Girth Welds that Require Special Consideration

11.4.1 General

There are two categories of pipe to pipe girth welds that require special consideration with respect to tensile strain capacity:

- Girth welds in thin wall Grade X70 pipe (see Section 11.4.2); and,
- Double-joint girth welds (see Section 11.4.3).

11.4.2 Girth Welds in Thin Wall Grade X70 Pipe

As noted previously SMAW girth welds in thin wall Grade X70 pipe present challenges due to thin pipe wall and the fact that the root pass and hot pass represent a significant proportion of the pipe wall thickness. As a result, even in cases where the fill-and-cap passes are made with SMAW LHVD consumables it is difficult to produce a matching or over-matched girth weld. This is particularly true if the root and hot pass are deposited with an E6010 SMAW consumable. Even in cases where the root and hot pass are deposited with an E8010 SMAW consumable there is still the potential for an under-matched girth weld.

An alternative option for Operators who are considering a thin wall Grade X70 pipeline design is to look at replacing the thin wall X70 pipe with either Grade X65 or Grade X60 pipe. A switch from Grade X70 to Grade X65 or X60 pipe provides the following two benefits:

1. The equivalent Grade X65 or Grade X60 pipeline designs will require pipe with an increased wall thickness which, in turn, will mean that the proportion of the girth weld associated with the root and hot pass will decrease.
2. A reduction in pipe grade (and pipe strength) will facilitate girth weld over-matching using an E8010 consumable for the weld root and hot pass.

If Grade X65 or X60 pipe is used the same limits on YS-L and TS-L should be applied (i.e., the maximum YS-L and TS-L should not be more than 17 ksi [120 MPa] above the specified minimum tensile properties).

11.4.3 Double-Joint Girth Welds

Double-joints are used in many pipeline projects to reduce the cost of pipeline construction. Double-joint girth welds are normally made using SAW to ensure high productivity, high quality welds at a competitive cost. SAW is generally a much higher heat input welding process than SMAW/FCAW so it will tend to produce girth welds with wider and softer HAZs raising potential concerns with HAZ softening, particularly on steels that are susceptible to HAZ softening.

Although SAW girth welds may contain wider/softer HAZs than SAW/FCAW girth welds, SAW girth welds are less susceptible to failures due to HAZ softening for these reasons:

1. The selection of SAW welding wires and fluxes generally produce high strength (over-matched), high toughness girth welds. As noted previously, girth weld over-matching protects soft HAZs and reduces the potential for failures due to HAZ softening.
2. SAW double-joint girth welds are normally manufactured using a double-V procedure (i.e., they are welded from the ID and OD). This double-V weld geometry is less susceptible to HAZ failures because it does not favor failures along a 45° slip plane.

12 Further Work

The JIP has produced guidelines to mitigate low strain failures in girth welds in Grade X70 pipe. However, there are additional studies that could be performed to strengthen the guidelines. These studies include:

12.1 Strain Aging of Grade X70 Pipe

The Grade X70 database developed in Phase 2 of the JIP is the most comprehensive database of Grade X70 pipe properties developed to date, with properties for SAWL, SAWH, and HF-ERW pipe from eight pipe mills, using steel produced by three plate suppliers and four coil suppliers. However, the database only contains data for pipe in the as-produced condition and is not representative of pipe properties in the installed condition, where the pipe will be in the strain-aged condition.

The Project Technical Team recommends that future pipe orders should include longitudinal tensile tests in the fully aged condition (250°C for one hour) during MPQT to determine the properties in the fully aged condition because this is the condition of the pipe during operation. In addition to collecting data from future pipe orders, the Project Technical Team recommends performing a study to characterize Grade X70 longitudinal tensile properties in the as produced and strain-aged conditions to determine how longitudinal tensile properties are impacted by strain aging, and if there are certain Grade X70 alloy designs that are more prone to strain aging.

The results of this study will help guide girth weld procedure development to ensure girth weld over-matching in the strain-aged condition (welding process and consumable selection).

12.2 HAZ Softening

Although the BOP tests performed in Phase 2 of the JIP provided clear trends, the BOP results were not sufficient to enable specific steel chemical composition limits to be developed to control HAZ softening due to:

- A limited range of Grade X70 materials; and,
- WT variation in the BOP specimens.

To develop specific composition limits, implementation of a comprehensive test program is required on Grade X70 steels with a wide range of chemical compositions. The BOP tests should be performed using Gleeble simulation to ensure consistent thermal cycles and consistent $t_{8/5}$ cooling rates.

The results of the Gleeble simulations can be analyzed to either confirm that Pcm is a suitable parameter to characterize HAZ softening or develop an alternative parameter to characterize HAZ softening. Gleeble test results should also permit specific chemical composition requirements to be established for future pipe orders.

HAZ hardness depends on chemical composition and rolling conditions particularly finishing temperature, water stop temperature and coiling temperature. The amount of niobium, molybdenum and vanadium remaining in solution in the final product can vary widely and affect the loss of strength or even lead to a strength increase but this variation cannot be quantified. However, its effect can be neutralized by tempering at 600°C for 30 minutes. It has been suggested that “The scatter in the plots of HAZ hardness or extent of softening with Pcm, CE etc. could be improved by applying a heat treatment, aging or tempering treatment at 600°C for 30 minutes prior to welding” and this should be considered if additional research (Bead on Pipe or Gleeble simulation) is undertaken."

13 References

This section lists references to this Draft Final Report.

1. API 1104, “Welding of Pipelines and Related Facilities”, 21st Edition, 2013.
2. CSA Z662-19, “Oil and Gas Pipeline Systems”, 2019.
3. API Specification 5L, “Line Pipe”, 43rd Edition, 2004.
4. PHMSA Advisory Bulletin ADB 10-033, 2010.
5. Ma J., “Effect of Strain Aging on Mechanical properties of Microalloyed X70 UOE Steel Pipes”, MSc Thesis, Dept of Chemical and Materials Engineering, University of Alberta, June 2016.
6. Gordon J.R, “Unpublished work linked to Arctic Strain Based Design Pipelines”.
7. Noecker R, Nissley N, Ma N, Thirumali N, Wojtulewicz P and Hukle M, “Strain Aging of C-Mn Line Pipe Steels: An Analytical Approach to Compare Strain Aging Heat Treatments”, OMAE Conference 2011, Paper OMAE2011-49917.
8. Australian Standard AS 2885, “Pipelines – Gas and Liquid Petroleum”, Part 1 “Design and Construction” and Part 2 “Welding”, 2016.
9. BS 4515-1, Specification for welding of steel pipelines on land and offshore – Part 1: Carbon and carbon manganese steel pipelines, British Standards Institution, 2009.
10. ISO 13847, Petroleum and natural gas industries - Pipeline transportation systems – Welding of pipelines, International Organization for Standardization, 2013.
11. AS2885.2:2016, Pipelines – Gas and liquid petroleum. Part 2: Welding, Standards Australia, 2016.
12. ASME Section IX, ASME Boiler and Pressure Vessel Code, Section IX: Welding and Brazing Qualifications, ASME International, 2017.
13. Gianetto, J.A., Bowker, J.T. and Dorling, D.V., Taylor, D., Horsley, D. and Fiore, S.R., “Overview of Tensile and Toughness Testing Protocols for Assessment of X100 Pipeline Girth Welds”, 7th International Pipeline Conference, Calgary, ASME, IPC2008-64668, pp. 1-10, 2008.
14. AWS B4.0, “Standard Methods for Mechanical Testing of Welds”, 2016
15. Dexter R.J. and Lundin C.D., “Plastic Behavior of Pipeline Girth welds with Softened Heat-Affected Zones and Under-Matched Weld Metal”, Mis-matching of Welds, ESIS 17, 1994.
16. Liu M. and Wang Y-Y., “Significance of Biaxial Stress on the Strain Concentration and Crack Driving Force in Pipeline Girth welds with Softened HAZ”, OMAE 2007-29415.
17. Pisarski H.G. and Dolby R.E., “The Significance of Softened HAZs in High Strength Structural Steels”, Welding in The World, Vol 47, No 5/6, 2003.
18. Denys, R “The effect of HAZ Softening on the Fracture Characteristics of Modern Steel Weldments and the Practical Integrity of Marine Structures made by TMCP Steels” EVALMAT 89, Kobe, Japan, 20-23 November 1989, ISIJ 1989 vol 2 pp 1013.
19. Mohr W.C., Gordon J.R. and Smith R., “Local Strain Accumulation in Pipeline Girth Welds”, IPC 2004 Paper IPC04-0474.
20. Ito, Y. and Bessyo, K., “Weldability Formula of High Strength Steels related to Heat Affected Zone Cracking”, IIW Document No. IX576-68, 1968.
21. Hamada M. et al, “Material Design for Line Pipe Steel to Minimize HAZ Softening and Obtain Good HAZ Toughness”, International Journal of Offshore and Polar Engineering, Volume 18, No 3, September 2008, p2014-210.
22. Denys, R.M. and Lefevre, T., “Effects of Welding on HAZ Softening of X70 / X80 TMCP Linepipe Steels”, PRCI Report PR-202-9635.

14 Alignment with Similar Industry Initiatives

14.1 General

Several initiatives that complement the JIP are currently underway across the pipeline industry. Section 14.2 briefly describes projects that are currently underway through PRCI International (PRCI).

An *Advisory Bulletin* was issued by the Department of Transportation related to the potential low and variable yield, and tensile strength and chemical composition properties in high strength line pipe. The bulletin:

> *Advises pipeline system owners and operators of the potential for high grade line pipe installed on projects to exhibit inconsistent chemical and mechanical properties. Yield strength and tensile strength properties that do not meet the line pipe specification minimums have been reported. This advisory bulletin pertains to microalloyed high strength line pipe grades, generally Grade X–70 and above. PHMSA recently reviewed metallurgical testing results from several recent projects indicating pipe joints produced from plate or coil from the same heat may exhibit variable chemical and mechanical properties by as much as 15% lower than the strength values specified by the pipe manufacturer.*

14.2 PRCI Initiatives

Three projects, currently underway through PRCI sponsorship, may provide valuable input to the JIP. Of these projects:

- Two are under the direction of the PRCI Design, Materials & Construction (DMC) Committee; and,
- One is under the direction of the PRCI Corrosion Committee.

The projects briefly described in sections 14.2.1 to 14.2.4 will be monitored. Collaboration between these parallel activities will occur where possible.

14.2.1 DMC: Implications of Low Strain Hardening Steels on Design, Construction and Maintenance (MATH-5-3)

In this project, the impact of low strain hardening on commonly-used design, construction, and maintenance practice will be examined. One of the tasks of the JIP is to identify high-priority practice, failure modes, or both in which strain hardening plays a critical role. The preliminary candidates are material specifications, hydrostatic testing, tolerance to mechanical damage, assessment of corrosion anomalies, and tolerance to accidental overloading (such as loads from ground movement). The project will assess risks associated with the above identified practice, failure modes, or both. The project will also recommend action plans for future assessment.

The overall objective is to understand the risks and benefits associated with the widespread use of modern microalloyed steels, which typically have lower strain hardening capacity than older steels. Materials with low strain hardening have reduced tolerance to flaws, accidental overloading, or other loads (i.e., from ground movement). Understanding this vulnerability will allow rational adoption of better practices in pipeline design, construction, and maintenance to keep risks at an acceptable level.

The impact of this work extends beyond design and construction to affect the entire life cycle of pipelines. Current pipeline design codes allow materials of up to Y/T=0.98 (before coating!). These materials are of great concern and it is expected that the results of this research will provide recommendations for changes to company specifications and international standards.

14.2.2 DMC: Guidance on the Use, Specification and Anomaly Assessment of Modern Line Pipe (MATH-5-3B)

This project is expected to achieve these objectives:

1. Develop a process to understand risks with use of modern line pipes/welding;
2. Mitigation/monitoring;
3. Welding practices, line pipe specifications, or both;
4. Identify anomaly assessment methods;
5. Recommended updates;
6. Create guidelines;
7. Identify tools for line pipe specifications and welding procedures; and,
8. Share data with standards committees.

The expected outcome from this project is to:

- Provide guidance on the proper use of modern line pipes and the application of welding processes to minimize the risk of girth weld failures; and,
- Recommend anomaly assessment methods for modern line pipe steels.

14.2.3 Corrosion: Applicability of Existing Metal-Loss Criteria for Low Hardening Steels (EC-2-8)

As background, prior research (EC-2-7) demonstrated the role of strain capacity on the failure pressure in metal loss defects. It also showed evidence of reduced failure pressure due to strain localization within the metal loss for lower hardening steels, and included the development of an extensive database of numerical analysis. Additional research (EC-2-5) also evaluated metal loss criteria for high strength steels.

14.2.4 DMC: Other Compatible Projects Completed (or Underway as Noted)

These compatible projects were completed or are underway:

- API-2-1, Full Thickness Weld Tensile Round Robin

  Validation of a test method to determine weld tensile properties using a near-full-thickness narrow strip specimen.
- CNST-2-2, Management of Pipeline Lifting and Lowering-in Stresses

  Guidelines have been completed and software implementation is underway.
- SBD-1-4, Assessment of Effect of Pipeline Wall Loss (Corrosion) on Strain Capacity
- MATH-5-2, Refined Methodology for Assessment of Weld High/Low Misalignment

- MATH-5-1, Guidelines to Address Pipeline Construction Quality Issues:
  - Addressed issues related to hydrostatic test failures of girth welds during new construction (repair and tie-in welds, in particular); and,
  - This guideline was the driver for several of the DMC projects described above.

14.3 Other Industry Initiatives

14.3.1 DNV-GL JIP: Standardization of Flattened-Strap Tensile Testing of Line Pipe

This project aims to develop methods to standardize flattened-strap pipe tensile specimens. Methods that will be explored include:

- The specification of influential tensile testing parameters; and,
- A standardized specimen for calibration of testing equipment and practices.

Tensile test results are a major contributing component to pipeline design and operation because a pipeline's strength must be suitable for containing the internal pressure of liquid or gas. The issue of inconsistent yield strength results from tensile testing of line pipe has been identified by Federal regulators in the US. The JIP will study the standardization of tensile testing parameters and calibration specimens.

Tensile test results from flattened-strap pipe specimens, which are a major component of pipeline design and operation, have been identified as inconsistent by Federal regulators in the US, and must be addressed by the industry.

Standardization of test procedures can minimize variability in yield strength results and their associated liabilities. As a result, improved test methods that establish accurate yield strength determination will minimize unanticipated pipeline project delays, and costs associated with new and existing pipelines. Furthermore, reduced variability in test results will allow pipe manufacturers and third-party test laboratories to provide test results that more closely reflect the actual distribution of pipe yield strength and are indicative of actual line pipe performance.

Each of these initiatives will be monitored and considered as part of the JIP.

15 Acknowledgements

The JIP Technical Team would like to acknowledge the JIP sponsors for their financial and technical contributions to the JIP.

In particular, the Technical Team would like to acknowledge the following individuals for the technical guidance and support they provided throughout the Project:

- Mr. Steve Rapp (JIP Chairman) — Enbridge
- Dr. Dave Johnson — Energy Transfer
- Mr. Dave Warman — *Retired from* Enterprise Products
- Mr. David Horsley — Horsley Consulting

Appendix A Terms of Engagement and Project Administration

A.1 Project Technical Team

The JIP Project Technical Team was responsible for finalizing the scope and deliverables, and execution of the JIP. As such, this Final Report presents the findings from the JIP Project Technical Team for use by the JIP Sponsors. The JIP Project Technical Team comprises:

- Robin Gordon, Principal Investigator — Microalloying International
- Yong-Yi Wang, Task Lead — CRES (Center for Reliable Energy Systems)
- Bill Bruce, Task Lead — DNV GL
- Malcolm Gray, Task Lead — Microalloyed Steel Institute
- Phil Kirkwood, Task Lead — Micro-Met International Ltd.
- Daniel Guzman, Project Manager — ITI International
- Patrick Vieth, Advisory — Dynamic Risk

The JIP Project Technical Team would like to acknowledge the following individuals for their Advisory contributions through the course of this project: Steve Rapp, Dave Horsley, Dave Warman, and David L. Johnson.

A.2 JIP Sponsor Representatives

This JIP was funded by 23 companies. Each of these companies designated one representative as the voice of their company. During the course of the JIP, JIP Sponsors were updated on progress and findings, and given the opportunity to provide input to the JIP Project Technical Team. This Draft Final Report represents the work of the JIP Project Technical Team, with appropriate consideration for input from JIP Sponsors and their corresponding organizations. The JIP Sponsors (or JIP Representatives) are:

- Steve Rapp, Chairman — Enbridge
- Jim Frost — American Steel Pipe
- Mehdi Fardi — APA Group
- Murali Manohar — Arcelor Mittal
- Frédéric Combaud — Berg Pipe
- Rodney Clayton — Boardwalk Pipelines
- Fatih Ozkan — Borusan USA
- Chris Williams — Cheniere
- Mark Anderson — Dura-Bond Pipe
- Dennise Loya — Energy Transfer
- Jake Haase — Enterprise Products

- Laurie Collins — EVRAZ
- Pepper Vance — Jindal Tubular
- Vickie Harthcock — JSW Steel USA Inc.
- F. Henry Martinez — Kinder Morgan
- Sara Maul — Marathon Pipe Line
- David Xu — PG&E
- Aidan (Yong Keun) Park — POSCO America
- Dan Edelman — SSAB
- Pankaj Mittal — STUPP
- Robert Lazor — TC Energy
- P.N. Mahida — Welspun Tubular
- Daniel Castro — Williams

In the event that any significant issue was identified during the course of the JIP (technical or otherwise), the JIP Sponsor was requested to raise the issue with either the JIP Sponsor Chairman, the Principal Investigator, or the Project Manager. Issues brought forward to the JIP Sponsors would be resolved through a simple majority vote from JIP Sponsors.

Additional JIP Participants from the JIP Sponsor companies are:

- Mark Fothergill — APA Group
- Terry Stamatiou — APA Group
- Wenkao Hou — Arcelor Mittal
- Dimitris Dimopoulos — Berg Pipe
- Todd Phillips (Borusan.com) — Borusan USA
- Daniel Whaley — Enbridge
- Gary Vervake — Enbridge
- Jake Phlipot — Enbridge
- Junfang Lu (Enbridge) — Enbridge
- David Johnson — Energy Transfer
- Liz Rutherford — Energy Transfer
- Dave Warman — Enterprise Products
- Eric Carlson — Enterprise Products
- Mohsen Mohammadijoo (EVRAZ NA) — EVRAZ
- Ramin Abolghasemi — EVRAZ
- Pankaj Mittal — Jindal Tubular
- Rama Krishna — Jindal Tubular

• Sanjay Pipalia	JSW Steel USA Inc.
• Todd Kedzie	Kinder Morgan
• Haferd, Jeffrey A.	Marathon Pipe Line
• Johnson, Sarah E.	Marathon Pipe Line
• David Aguiar	PG&E
• Dr. Soon Gi Lee	POSCO America
• Young-Hwan Park	POSCO America
• Park Yong Keun	POSCO America
• Nelson, Todd	SSAB
• Aaron Litschewski	STUPP
• Lee Everett	STUPP
• Alan Morton	Williams
• David Katz	Williams
• Harvey Stockman	Williams
• Sean Moran	Williams

Appendix B JIP Sponsor Letters

B.1 JIP Sponsor Letters – Letters of Support

Enbridge
5400 Westheimer Court
Houston, Texas 77056

Reflections on the JIP

I'd like to thank all the contributors to this Joint Industry Project (JIP), particularly the technical experts working under the direction of Robin Gordon and Patrick Vieth. But also, many thanks to the sponsors for their time, input, data and collaboration. The collective input from the full industry food chain (steelmakers, plate and coil manufacturers, pipe suppliers and pipeline operators) has brought a full perspective of the issues related to these failures.

The pipeline industry has recently experienced a high frequency of failures of newly built pipelines. The forensic work performed by the JIP demonstrated that girth weld undermatching was a primary contributor to the cause of failure, either due to under-matched weld metal strength or excessively softened girth weld heat-affected zones relative to line pipe with excessively high longitudinal strength.

The recommendations contained within this report to avoid under matched welds are both obvious and intuitive: lower the pipe longitudinal strength, increase the weld metal strength and minimize weld HAZ softening. The recommendations regarding maximum longitudinal strength limits, minimum alloy content limits, and higher strength low hydrogen girth weld consumables will require industry-wide commitment. However, the commitment for change begins with pipeline operators to revise purchase specification requirements for X65/X70 line pipe and construction specifications to eliminate to current practice for E6010/E8010 girth welds.

The recommendations were not developed without controversy. JIP members that are critics and opponents of the recommendations being formally promulgated by the JIP, cite higher material and construction costs as the basis for their opposition but fail to fully recognize the implications of further failures (safety, direct and indirect costs associated with failures, and the ability to obtain and maintain a license to build and operate new pipelines). Although the JIP's recommendations for pipe strength, composition limits and field welding practice changes differ from current industry practices, the option to continue down the same path and do nothing in hopes of finding an easier/better solution in the future is simply a non-option.

Enbridge has already implemented the above changes to both the pipe purchase and construction specifications. Furthermore, Enbridge will strictly adhere to these changes with very little latitude for exceptions. As these changes are applied industry-wide, steel processing solutions will be developed to meet these requirements and construction contractors will become proficient with these higher strength consumables. Implementing these changes by owner/operators will go a long way towards eliminating these types of girth weld failure events.

As further research and work is performed, some refinements to strength and composition limits may be possible. Further work in this area is planned and is certainly needed. However, in the meantime, these JIP findings stress that the above stated changes are needed to enhance the safety and reliability of new pipeline construction.

Again, many thanks to all that contributed to the success of this JIP.

Steve Rapp P.E.
JIP Chairman

Energy Transfer Operator Letter for X70 JIP

We went for decades without anything resembling systemic girth weld failures. Now, in more recent years, there have been a number of early-life failures, both during testing and in service, that were due to properties, not due to defects in either the weld or the pipe or due to unusual loadings. The number of these failures and the common characteristics noted during their investigation led to this JIP.

Strain concentration in the girth weld region (the weld and its associated heat affected zones) has been determined a primary or strong and evident contributing factor in these failures. Strains that might normally, and have previously, been accommodated along the 40 to 80-foot length of pipe have now been concentrated into an inch or less of length, greatly exceeding the capability of the steel to accommodate that much strain. So we get failures. The JIP sought to study this and develop mitigation strategies from two sides – simply put to make the welds stronger and make the pipe weaker. This approach is logical, but is complicated a bit by the potential for the HAZs to become the absolutely weakest part of the structure due to softening during welding.

The answers, the interim recommendations, that the JIP reached based upon the limited time, materials and resources available, addresses these three contributors and asks all stakeholders – steel and pipe manufacturers, construction contractors and pipeline operators – to make some changes to be part of the solution rather than perpetuators of the problem.

These boil down to:

1. Reduce and control the maximum longitudinal pipe strengths to a level that can be overmatched by the girth welds.

2. Reduce the HAZ softening propensity of the pipe by maintaining a slightly richer, more hardenable chemistry.

3. Change welding practices and consumables to produce stronger welds at somewhat lower heat inputs.

The commitments required are for the steel and pipe producers to make some adjustments in their targets and “recipes” to achieve the modified performance requirements, for the pipeline construction contractors to become proficient at welding processes and with welding consumables that have not been traditionally used on domestic pipelines, and for the pipeline operators to specify and be willing to both enforce those specifications and pay any incremental costs that may be associated with these changes.

If further work provides additional insights and more effective solutions, we will all certainly entertain those. However, the status quo is not acceptable to the operators, our regulatory agencies or the public. The recommendations coming from this work, while admittedly not perfect, are our best path toward improved performance at this time.

1300 Main St | Houston, Texas 77002 | (713) 989-7000

There is a problem. It needs to be addressed now, using the best knowledge and insights we have. Those are embodied in the work done during this JIP. There's an old adage about being either part of the problem or part of the solution. Denying the existence of a problem or resisting having to make any changes in response to it demonstrates an effective willingness to let the problem continue. We are asking all parties to be part of the solution, and hope that they will be.

1300 Main St | Houston, Texas 77002 | (713) 989-7000

Integrity and Corrosion Engineering

Marathon Pipe Line LLC

539 South Main Street
Findlay, OH 45840
Tel: 419.422.2121

May 8, 2020

To: Project Managers
RE: Joint Industry Project,
Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines

In order to assist the Oil and Gas industry in preventing future failures in pipelines of high strength materials and continue to grow our company's technical expertise in welding, Marathon Pipe Line (MPL) has supported the Joint Industry Project: Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines. Some of the factors specifically focused on by technical experts at Marathon include girth weld undermatching, heat-affected zone softening, welding consumable selection, and welding procedures. With the research completed so far, there is better understanding as to how these factors work together and can be optimized to mitigate failures in high strength pipelines. While MPL does not have substantial history working with high strength steels, this study has aided MPL's Integrity and Corrosion Engineering Department develop knowledge and understanding in high strength steels and their risks when using them for new pipeline systems. As the results of the project demonstrate, there is not one simple solution when welding high strength steels in pipeline applications. MPL will continue to review the results of the study and perform additional work in welding electrodes, pipe grade transitions, and tensile testing to further advance its knowledge to make educated decisions on use of high strength steel for pipelines. Conducting further testing in these areas will allow MPL to increase engineering flexibility and to improve the integrity of welds for these materials.

Even more importantly, this study brought together multiple pipeline operators and pipe material manufacturers, allowing for consideration from multiple perspectives. Manufacturing practices of the steel and then testing those materials to the criteria outlined by the project helped create guidelines to mitigate the effects when welding. These guidelines will help improve pipe production and procurement standards. The same is true when testing and outlining welding considerations for both consumables and joint geometry. Further work will build on this knowledge, including additional data collection of pipe properties, so that more welding tests can be conducted to further understand the effects of weld strength when joining high strength materials. With additional data, industry participants can better understand high strength steel pipe and use it to it is full potential, while mitigating risk to pipeline systems.

Thank you,

Justin Stiles
Integrity Quality Assurance Supervisor

TC Energy
450 - 1 Street SW Calgary, AB
Canada, T2P 5H1
Tel: 403-920-5679
robert_lazor@tcenergy.com

May 11, 2020

Re: TC Energy Perspective to the JIP Final Summary Report:
Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines, 20 April 2020

This letter presents TC Energy perspective on the work completed during the execution of this project. TC Energy agrees with the general conclusions that HAZ Softening is a serious industry concern and we view that this report can be used as a basis for additional work.

TC Energy does not approve this report for external release.

The comments are broadly divided into perceived gaps and other items where we generally agree with the results of the work.

Gaps

1. The review of the failure investigations provided little information, reporting only that the pipe met API 5L and the welding procedure met API 1104 requirements, raising concerns whether the current standards alone are sufficient to prevent this type of failure. A common theme of the failure incidents was the use of welding procedures that were undermatched for the properties of the pipe being welded and HAZ softening. However, it is unknown if there were other root causes or contributing factors that may be pertinent to the development of effective mitigation strategies against this type of failure. Requirements for pipeline operators to supply weld procedures, welder qualification records, and weld parameters for girth weld failures should be considered to enable appropriate root cause analysis investigations.
2. The Phase 2, Task 1 report on pipe properties showed many pipe chemistries that had less than 0.04 C and less than 0.14 Pcm, yet these observations had not been brought forward to the summary reports, and consequently a large percentage of pipe considered by the JIP would be excluded. A new equation, or further guidance, to predict HAZ softening is needed; however, this may be difficult given the range of TMCP processes and their influence on softening susceptibility.
3. The report lacks a discussion that relates chemical composition, steelmaking practice, and TMCP processes to the tensile properties and susceptibility to HAZ Softening. Controlling chemistry on its own without also considering steelmaking and pipe manufacturing may not prevent softening, and therefore the end user is not able to address these issues in their proprietary specifications.
4. The management of pipe strengths makes sense to prevent significant undermatching of weld metal strength; however, the arbitrary 17 ksi above specified minimum values does not appear to have an established technical basis. It is noted that some of the industry failure examples occurred despite meeting this recommended strength limitation.
5. While the report identified several elements of weld design, namely filler metal strength and weld cap profile, additional elements of weld design may need to be considered in a more

holistic approach to prevent this type of failure. Consideration should be given to require pipeline operators to have a competent engineer review weld designs to ensure they meet site conditions and that appropriate restrictions on inputs are outlined for welding procedures.

6. TC Energy are concerned that the heat input limitations recommended in this report are not founded on a sound technical basis and may prove overly restrictive for some commonly used manual and semi-automatic welding processes.

In Agreement

1. The failures are associated with manually welded pipe only.
2. The failures reported in the JIP generally describe a problem due to girth weld undermatching and HAZ softening.
3. Two of the three recommendations (weld to achieve overmatch, minimize HAZ softening) should be considered as required for all pipeline welds. The third (reduce pipe strength) is considered as optional, provided strength meets the requirements of the applicable standard.
4. Operators should account for the longitudinal properties in the strain-aged condition, in order to develop suitable welding procedures.
5. CWT tests should fail in the base pipe or have sufficient tensile strain capacity for the intended design. TC Energy recommends CWT with reinforcement, however acceptance criteria for simple cross-weld tensile tests needs to be determined.
6. Furthermore, it should be mandatory to perform AWMT for all qualifications.
7. Tensile properties of recent pipe materials tend to be higher than those for pipe from previous generations. This is in part due to increased use of SAWH pipe, although it has been used for nearly the past 50 years without similar incidents. The recommendation to use the highest strength pipe on a given project is not always possible and can lead to problems upon audit. The extra cost is generally not warranted, particularly on small projects.

Robert Lazor, P.Eng.
Principal Engineer, Welding & Materials Engineering
TC Energy

EVRAZ NA Comments on the JIP Phase-2 Final Summary Report

Mohsen Mohammadijoo (Welding and Materials Research Engineer – R&D)
Alex Afaganis (Director – Tech Services)

General Statement on the Report

The report provides some invaluable information and analysis obtained considering the following criteria:
- SAWL, SAWH and ERW pipe tensile properties
- Tensile testing of all-weld and cross-weld samples
- Welding heat input and weld cap size (experimental and FE modeling) effect on girth weld failure
- Weld strength under-/even-/over-match and recommendations on alternative electrodes for achieving weld over-match

EVRAZ NA would like to state that the summary report on JIP phase-2 is accepted subject to the comments mentioned below.

General Recommendations/ Guidelines to Mitigate Low Strain Girth Weld Failures

EVRAZ wishes to clarify that these guidelines [P.7 (recommendations) & P.92 (section 11.3)] identify factors which can influence local weld strain and that recommendation limits in many cases are lines in the sand based on limited information. To achieve an "optimized" design one must account for and balance factors such as the expected weld strain/load expectations, pipe and weld strength limits, HAZ properties/size, weld design, welding ease/efficiency, impact of alloy content on toughness/strength/cost, and many other factors that may influence the pipeline design. This optimized approach was presented by Bill Bruce at API 1104/5L joint meetings showing hard and soft requirements depending on pipeline conditions as well as pipe/welding design requirements.

EVRAZ recommends that guidance [P.87 (section 9.2)] should be framed in decision process flow diagram of the various variables which can impact susceptibility to the failure conditions. This would be in line with the recommendations of Table 22 and 23 defining optimum balance of key factors to meet target properties and resistance to localized straining.

Pipe Tensile Properties

This study noted that it collected the one of the largest collections of transverse and longitudinal tensile data. The analysis in P.34 (section 6.2.1 5th bullet) and P.36 (section 6.5 2nd para., 1st sentence) do not support the achievement of the proposed SMYS/SMTS + 17 ksi limits in helical SAW or HF-ERW pipe (Figures 5 and 6). For example, SAWH pipe average YS-T is 76.6 ksi with a std. dev of 2.8 ksi. This average is already within 3 std. dev of the minimum and can't be pushed lower. Further, as the flattened strap transverse yield strength is over 6 ksi lower than the longitudinal strength the ability to consistently achieve the longitudinal strength limits appears not possible with this data set. This is supported by Table 9, which shows 95% capability at around 20 ksi above both SMYS implying a 2.5% failure rate for both HFW and SAWH. Based on this work from a capability perspective, the following limits would more align with the data presented YS-L = SMYS + 22 ksi and TS-L = SMTS + 20 ksi.

In the recommendations on P.7, P.36 and P.92 the statement that SMYS or SMTS + 17 ksi longitudinal tensile limits have been met by two SAWH mills on several pipeline projects may not represent the full story. EVRAZ understands that an allowance was made for over strength pipe (5% of the order could exceed the cap). This allowance aligns with the statistics presented in Fig. 5 and Table 9 and is in line with current experience. Consideration for this in customer specifications should be made as manufacturers gain experience with this new longitudinal strength capacity parameter as pipe mills gain experience over the full range of their product offerings.

Tension Test Specimens

The tone of the clauses on P.7 (last para.) & P.36 (section 6.5 2nd para.) imply that pipe mills have an option to test with alternate techniques but have chosen not to act. This needs to be clarified. It should be noted that many line pipe purchasers/users will not permit round-bar tension tests (let alone ring expansion) due to the inherent conservative nature of the test, and purchaser specification limits have been tuned to flattened strap limits (Y/T max). The option of conducting compliance testing with round bar may also require retooling of test labs to keep up with production testing release. Ring expansion testing while interesting on a research basis has never been used as a production test due to precise machining, preparation and logistic issues.

HAZ Softening and Pcm Limits

EVRAZ agrees that the final HAZ hardness is primarily a function of steel composition and heat input, but the stand-in for composition (Pcm) is not appropriate for this measure as it is more a measure of predicting CGHAZ peak hardness not general HAZ softening. Softening appears to be also strongly tied to grain boundary pinning and microalloy design in addition to solid solution and transformational effects. EVRAZ will be presenting a paper at IPC 2020 investigating microalloying affects.

In the recommendations on P.9 (2^{nd} and 3^{rd} para.) & p.71 (3rd para.) there is a statement that "no firm recommendations can be made on steel composition limits to mitigate HAZ softening without additional testing" however the report goes on to state that "...HAZ softening increases as Pcm decreases. As a result specifying a minimum Pcm (e.g., >0.14) may also help to mitigate HAZ softening." This is not supported by the data presented and the later statements relating to Pcm minimum are inappropriate. Further a caution should be added that excessive values of Pcm can translate into high HAZ hardness which may detriment toughness, and a balance is required for optimum properties. There are some other issues within the body of the report including:

- The factors influencing HAZ softening [P.22 (section 4.2 1st para.)] – These are not well defined in the literature and those listed are only suspected contributors as the literature survey in Phase 1 did not offer any commentary on these factors. Further the list presented do not consider important factors such as micro alloying optimization.
- The basis for choosing 0.14 min Pcm [P.57 (1st para.) & P.94] is arbitrary and not well explained / supported (especially for HI <1-1.5 KJ/mm). In one case, a 20% hardness drop from a high Pcm (0.21) was presented but this has little basis. Later there is proposal to set 150 HV as a reasonable minimum (Figure 9) to support a Pcm of 0.14. It is also flawed as it was earlier explained that it is the difference in the hardness between the base metal and the HAZ that is critical, not the minimum value.
- The results presented in P.76-Fig. 19 and P.58-Fig. 9 indicate a significant scatter in the data with no obvious trend in the level of HAZ softening vs. steel's C content and Pcm.
- The correlations presented are most applicable for higher heat inputs [P.59 (section 8.3 last para.) and 67 (4th para.)] - As the recommendations (P.9 #8, & P.94) limit maximum heat input to <1.0-1.5 KJ/mm, the correlations to Pcm are not significant at these heat input.
- Although the BOP technique aligns with API RP 2Z, this method is not a sufficient method for studying the susceptibility of steel to HAZ softening as it simulates the upper weld pass (with no joint bevel), whereas the softening is more critical towards the root and hot passes, due to the different heat transfer phenomenon in the lower passes in compare with the upper passes. The R2 values presented in Table 22 indicate no/little statistically valid trends other than those from 2 kJ/mm welds. In addition, the size and level of HAZ softening might also be affected by the different WTs studied here (as also shown in Fig. 12).

Girth welds that require special considerations

The scope of this discussion and analysis was associated with X70 pipe with secondary impact on X65 and there was no significant discussion about X60. The X60 strength limit recommendations on P.9 are not supported and strength capability analyses were not completed. If such lower grade limits are to be considered in the final recommendations on P.95 section 11.4.2, the SMYS/SMTS + 17 ksi maximum strength limits should be loosened to say +22 ksi due to the pipe/weld overmatch ratio being naturally lower due to a lower average pipe strength.

The criteria for thin wall pipe (<0.375") is arbitrary and further research is required to define this threshold wall thickness value.

Miscellaneous

WPS/PQR test pipe selection (P.38 – 2^{nd} para.) - The proposal to identify and test the highest strength heat presents significant logistical issues especially for a long order. Consideration should be given for choosing pipe from test units within say the highest 5% pipe strength lots.

ENHANCED GIRTH WELD PERFORMANCE FOR NEWLY CONSTRUCTED X70 PIPELINES [FINAL REPORTS DATED APRIL 20th, 2020]

Williams has rigorously studied the content of the Final Draft summary report and the details contained in the Final Draft of the Phase 2 Task reports. The following comments are made on behalf of Williams. Throughout the extensive investigation and the analysis of its results, we have been in dialogue with key experts on the Project Lead Team and the following offer Williams views, interpretations, and understandings from those interactions.

From the beginning of the JIP, all sponsoring and participating entities unanimously shared a critical concern: how to avoid the next pipeline failure, especially one attributed to HAZ softening. A great wealth of invaluable data has been generated by this important JIP project, and some excellent analytical work has been completed. However, the absence of unanimity amongst the industry experts on the Project Lead Team and within the JIP sponsorship has created concerns on certain report recommendations.

The prevalent expertise in steel manufacturing lies within the industry's established steel manufacturing experts and within the steel and pipe manufacturers themselves. In general, the industry experts and manufacturers understand the detailed intricacies of their own equipment and processes better than any single pipeline operator can.

One recommendation made in the report to restrict Pcm has created contentious debate within the JIP. Such a restriction may have potential unconsidered effect on other mechanical and chemical properties, especially carbon content, of line pipe steels and further investigation is warranted to satisfy this concern. By adding restrictions to Pcm, the entire target chemistry is significantly altered and may result in a substantially different chemistry than the line pipe steel chemistries that were used in this study, even whilst meeting the proposed restrictions. Such changes made to modern, microalloying, and steel making technology should necessitate considerable dialogue between experts, manufacturers, and operators to better understand any potential unconsidered effect.

Compelling evidence presented to the JIP sponsorship indicated the likelihood of HAZ softening could be substantially reduced by changes to commonly used welding procedures. More specifically, changes to weld heat input, welding consumable selection, and weld geometry. These changes can be implemented immediately and their effect in HAZ softening is considerably more conclusive and immediate as compared to chemical composition limits based on data presented to the JIP. To highlight this point 2 out of 3 of the most disconcerting girth weld failures studied [Nos 5 and 6] had Pcm's of 0.156 and 0.165 respectively [well above 0.14].

Please consider the following observations:

- The JIP reports contain extensive statistics of X70 production over the last decade from which it has been conceded that 20% of all SAWH pipe had a Pcm ≤ 0.14. The equivalent figure for HF-ERW was even higher at 50% (see table 9 on Page 39 of the Task 1 report). Furthermore 18% of SAWH pipe revealed a carbon level ≤ 0.04% with 3% ≤ 0.03% carbon (Table 8).

- The statistics above, derived from voluminous data, could be interpreted to suggest that the JIP recommendation to restrict Pcm to ≤ 0.14 potentially questions the 'fitness for purpose' of girth welds in tens of thousands of miles of pipe that have been installed and are successfully operating in North America.

- In the reports, much importance is attached to a percentage softening in the HAZ of ≥ 15% but, in the BOP tests at the highest heat input (2kJ/mm), this result was not unique to low Pcm steels. Steel 58003 had a Pcm of 0.155 and a carbon content of 0.065 yet softened 40 points Vickers from its average parent plate hardness.

- Notwithstanding the attempts on Page 26 of the Task 5 report to validate the BOP results, other evidence demonstrates that the sub-surface hardness data was significantly influenced by wall thickness impacting on both the absolute hardness recorded and the width of the softened zone of the HAZ.

- In Section 7.3 of the Task 5 report, at the foot of Page 39, provisional limits are proposed to control HAZ softening to less than 20%; these are Pcm ≥ 0.14 and weld heat input ≤ 1.5kJmm. However, as revealed in Table 7 on page 37 of the Task 5 report, only one data point from the whole exercise occurs where the 20% figure was exceeded. Moreover, for this data point, both the previous bullet point and the fact that 1.5 kJ/mm was not a heat input studied call this result into question.

- Page 35 of the Task 5 report suggests that "Although Pcm appears to provide a reasonable indicator of HAZ softening, the results exhibit scattering indicating that Pcm may not be the ideal parameter to characterize HAZ softening".

In conclusion, Williams will strongly consider all the recommendations made in the report in a continued effort to maintain the safety of the public and property in the locations where it operates its assets. Safety is Williams' highest priority and is accomplished, in part, with a continued focus on long term integrity of all assets. The recommendations that will have the most positive impact on this focus, and without potential detriment to other components of asset integrity, will be implemented to the extent practical.

B.2 JIP Sponsor Letters – Letters of Concern

ArcelorMittal

To:
Patrick Vieth
Robin Gordon
Principal Investigators
JIP "Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines"

May 11, 2020

Dear Patrick, Robin:

ArcelorMittal votes to **'DISAPPROVE'** the final summary report, especially its recommended changes in material specification as written . Our position is based on the following rationale:

1. ArcelorMittal's participation in the JIP was based on the initial claim that there was overwhelming evidence showing the need for changes to material specifications to avoid failures due to girth weld softening in X70 pipelines.
2. However, the data collected and presented as well as the discussions that took place during the course of the JIP failed to show a correlation between field failures and material composition and properties.
    - In fact, data presented showed failures even in X70 welds where the pipes would have met the proposed specification limits.

Establishing a minimum Pcm value to limit HAZ softening

3. CE (Pcm) – the data presented does not show a clear correlation between Pcm and HAZ softening. When the data is sorted on the basis of thickness, there is no correlation between Pcm and HAZ softening. Nevertheless, ArcelorMittal can accept 0.14 minimum CE (Pcm) requirement on the standard application X70M internal (non-sour service) grades.

Establishment of maximum values for Longitudinal YS and UTS

4. The proposed limits on longitudinal YS and UTS are based on finite element simulations and not real weld data and are practically unattainable while trying to consistently meet the transverse SMYS. The statistics presented in Figures 5 & 6, and Table 10 **do not** support the achievement of the proposed limits in helical or HF-ERW pipe. Until acknowledged issues with pipe testing variation T-YS, described in 4.3 Pipe Material Strength can be resolved to supplier and end user satisfaction, ArcelorMittal will take the following positions:

ArcelorMittal
Global R&D – East Chicago
3001 East Columbus Drive
East Chicago, Indiana 46312

T (219) 399-7753
F (219) 399-3899

www.arcelormittal.com

- **<u>Proposal 1</u>**
  ArcelorMittal proposes the following limits YS-L = SMYS + 22 ksi and TS-L = SMTS +20 ksi.
- **<u>Proposal 2</u>**
  ArcelorMittal would be agreeable to YS-L = SMYS + 17 ksi for an allowance or waiver for 20 percent of the pipe tested over the restricted maximum, but within full API; and,
  ArcelorMittal would be agreeable to TS-L = SMTS +17 ksi for an allowance or waiver for 10 percent of the pipe tested over the restricted maximum, but within full API.

5. **Disagree** with setting the new limits of +17 ksi for YS-L and TS-L to apply for X65 and X60. 11.4.2 Girth Weld in Thin Wall Grade X70 Pipe. The scope of the JIP was defined as X70 Pipelines.

6. ArcelorMittal believes that the failures due to girth weld HAZ softening are **primarily welding-related**. Use of higher strength consumables to eliminate undermatching, lower heat input to reduce potential of softening, tighter quality control procedures to assure more uniform practices will eliminate such failures. In Europe where the welding is under better control, this problem does not exist.

7. Additionally, as stated earlier, accepted alternatives are needed to resolve issues with pipe testing variation T-YS, described in 4.3 Pipe Material Strength.

Let me know if you have any questions.

Regards,

Murali

Murali Manohar

ArcelorMittal Global R&D - East Chicago

T +1 219 399-2556| **F** +1 219 399-6562| **M** +1 610 653 0034| murali.manohar@arcelormittal.com

Berg Pipe
A Company of the EUROPIPE Group
5315 West 19th Street
Panama City, FL 32401
Main: 850-769-2273
Direct: 251-330-2873
www.bergpipe.com
Email: frederic.combaud@bergpipe.com

Frédéric Combaud
Quality Control Manager Berg Pipe Mobile
Welding Engineer

May 11, 2020

To: Robin Gordon, Steve Rapp, Patrick Vieth
JIP Technical Team
Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines

Subject: BERG PIPE comments to final report

Although Berg Pipe agrees that the under match is an important contributor to the girth weld failures, we are concerned with the introduction of strict maximum limits for the longitudinal properties of pipes. Previous work (JIP and other) has shown that determining the yield strength of pipes with transverse flattened specimen exhibits significantly variability and generally speaking the measured strength is less than the actual (determined by the use of non-flattened specimen methods such as round bar specimens or ring expansion). Since use of longitudinal specimens is not affected as much from the flattening process, trying to respect minimum yield strength limit on the transverse direction and maximum limit on the longitudinal is particularly difficult for helical seam pipes. Efforts to adjust the strength on coil or pipe so it meets both above conflicting requirements is challenging and Berg Pipe's experience has shown that the whole process is extremely sensitive to <u>minute process variations in steel making and/or coil rolling that can have a drastic effect to quality of pipes.</u>

Conclusively, Berg Pipe believes that, while the adoption of strict maximum limits for the longitudinal properties of pipes may not be sufficient to prevent future girth weld failures, it creates new issues of potential compliance of pipes meeting the SMYS together with all associated complications that come with it for the industry. Alternatively, Berg Pipe's proposal to address this issue are:

1. Use of higher-grade welding electrodes for girth welds (basic low hydrogen electrodes instead of the cellulosic electrodes for all passes – root/hot/filler/cap) already successfully implemented in other markets, and/or
2. Consideration of non-flattened specimens for the determination of yield strength (eg round bar specimens).

Sincerely,

Frédéric Combaud
Quality Control Manager Berg Pipe Mobile
Welding Engineer

DURA-BOND

Date: 5-11-2020

To: Patrick Vieth
From: Mark Anderson, Director of Quality, Dura-Bond Pipe, LLC
cc: Jason Norris, President, Dura-Bond Pipe, LLC

Subject: Comment on Final Summary Report – JIP Enhanced HAZ

The following comments pertaining to X70M pipes produced from plates rolled with TMCP and the recommendations in the Final Summary Report "Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines"

Proposed recommendations and comments:

1. Section 11.3.1

The recommendation for pipe longitudinal properties produced from plates to meet the transverse properties is problematic for the majority steel grade used for pipe orders of 0.625" gauge and less with -4F test temperature or higher for Charpy testing. Experience with longitudinal testing indicates this grade is capable of meeting the recommended maximum YS-L limit of SMYS +17 ksi for X70M, but will marginally fail the minimum YS-L at a 10-30% rate unless the YS-T aim is increased by 3 ksi or more. By doing so, the restricted maximum YS-T, that could otherwise be accommodated, has a risk for being exceeded at a low percentage. The average YS-T that is typically 76-78 ksi would be increased to 79-82 ksi to achieve the recommended minimum YS-L. This grade is currently rolled to an aim UTS due to the hydraulic expansion process and therefore would need to be increased. There is a likelihood of reduced Charpy impact energy by increasing of the YS-T and UTS-T to meet the longitudinal properties.

A melt grade option exists that has less strength loss in forming and continuous yielding behavior during expansion, but has not been utilized in gauges less than 0.480". It is available for thinner gauges, though. This grade has been utilized for elevated impact energy at -18°F test temperatures and 14°F DWTT for gauges primarily of 0.515" to 0.750". The longitudinal properties for YS-L and UTS-L can be achieved with this grade given an allowance to exceed SMYS+17 ksi by 2 ksi for 5% of heats for project size orders.

2. Section 11.3.3

The recommendation to specify a CE Pcm greater than 0.14 (0.15 minimum) is not compatible with the grades best suited to meet the YS-L minimums from domestic and foreign sources. A 0.14 Pcm is frequently received with average Pcm near 0.16. A 0.14% Pcm with applicable rounding rules can be accommodated with domestic and foreign source.

The melt grade with the greatest production experience can meet the 0.15 Pcm minimum for X70M for both heat and product analyses, but has exceptions to the recommended minimum YS-L.

Joint Industry Project (JIP) Final Summary Report
Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines
SSAB Americas Perspective Statement

SSAB Americas, a JIP Sponsor, is the largest producer and supplier of heavy plate in North America, with a market share of approximately 27% in 2019. SSAB's modern steel mills are located in Mobile, Alabama and Montpelier, Iowa and have a combined annual production capacity of 2.4 million tonnes. Both steel mills utilize a scrap-based, electric arc furnace (EAF) method to produce steel and Steckel mill rolling technology to produce both plate and coils for skelp for line pipe manufacture. To increase our capacity to produce premium steel grades, principally for the line pipe market, SSAB has also recently invested in MULtiPurpose Interrupted Cooling (MULPIC) technology at our Mobile, Alabama steel mill.[1]

Focusing on the guidelines of the JIP which are related to plate and coil skelp production, and therefore of most relevance to SSAB Americas' operations, we have significant concerns with both the recommendation for limits on pipe longitudinal tensile properties and the suggestion to specify chemical composition restrictions such as 0.04% minimum carbon content and a Pcm > 0.14.

Relative to the recommendation to impose maximum longitudinal yield strength and longitudinal tensile strength of SMYS + 17 ksi and SMTS + 17 ksi, respectively, we note that the JIP's own database of longitudinal pipe tensile properties demonstrates that 10% of the SAWH and HF-ERW pipes fail to meet the SMYS + 17 ksi, in the as-produced pipe. Should the recommended maximum longitudinal tensile properties become codified, this failure rate would be unacceptably high and result in substantial increased costs for steel mills, pipe mills, and pipeline operators. Furthermore, if testing is eventually mandated in the aged condition without any change in the current practice of over-specifying minimum skelp yield strength due to the Bauschinger effect on flattening transverse pipe strap tensile specimens, assuming the projected 3 to 10 ksi increase in pipe longitudinal yield strength with aging, the percentage of tests exceeding the SMYS + 17 ksi limit would be approximately 37% for SAWH and 5% for SAWL pipe for a 3 ksi increase in the mean longitudinal yield strength with aging and roughly 95% for SAWH and 64% for SAWL for a 10 ksi increase in mean longitudinal yield strength with aging. Such a failure rate is unsustainable for all parties. We agree that pipe transverse tensile properties should be measured by alternative methods, such as round bar specimens. Currently pipe mills over specify minimum skelp yield strength by 5 to 6 ksi in order to avoid failing pipe yield strength due to the Bauschinger effect. This practice impedes the development to produce girth weld over-matching by unnecessarily increasing tensile properties in X70 pipe. Once the true properties of the pipe are measured then the capability to meet the proposed pipe longitudinal yield strength and longitudinal tensile strength may be more robust, at least in the as-produced condition.

[1] SSAB Capital Markets Day 2019 Presentation,

With respect to the effects of chemical composition on HAZ softening, we strongly agree that the results of the bead on plate and girth weld test programs do not demonstrate sufficiently strong correlations to support any firm recommendations for a minimum carbon content nor a minimum Pcm value to mitigate HAZ softening. Again, should such restrictions on skelp chemical composition be codified, there would be potential cost implications in terms of material rejection without a compelling and demonstrated benefit for mitigation of HAZ softening. It is important to note that advances in steel production technology have allowed skelp producers to achieve pipe strength requirements while delivering excellent toughness and improved weldability through metallurgical approaches that use leaner compositions. Imposing chemical composition restrictions without strong evidence marginalizes the full potential of such technologies. We concur that this is one area in which additional testing is needed. Such ongoing investigations should also include how welding parameters influence HAZ characteristics so that pipeline construction companies have better information to optimize control over both the pipe specification and the welding procedure specifications. In the interim, the results of this JIP show that controlling girth weld heat input will be the most effective method for mitigating HAZ softening.

We recognize that the recommended JIP limits on pipe longitudinal tensile properties and the suggested chemical composition limits have been, and continue to be, cited in project specifications and pipe mill purchase orders. As such these requirements allow for negotiation between pipe line owners and operators, pipe mills and steel mills based on the specific capabilities, equipment, and technologies of all the parties involved. We believe that this ability to negotiate such “guardrails” along with implementation of the additional JIP recommendations related to girth welding practices and processes, will serve to mitigate the risk for low strain girth weld failures. This will also allow time for additional research outlined in the JIP’s Further Work section.

SSAB Americas’ participation in the market for plate and coil skelp for line pipe is important to our business and we continue to strive to deliver exceptional value to our customers in this segment. We remain willing to contribute our experience and expertise to support industry efforts and initiatives to enhance the quality and integrity of pipelines.

Stupp

Comments on Final Draft Report

The draft report was reviewed, and our major concern is on max. limits on the long. Tensile properties. Each pipe manufacturing process has different properties starting from plate/HR coils to Pipes.

For Spiral pipes, the tensile properties are higher in Long. Direction than in Transverse direction due to pipe forming angle. The Transverse of pipe is around 45 deg of the coil rolling direction. The long. Axis of pipe is mostly transverse of the coil rolling direction. As we know the coils have higher properties in Transverse direction than 45 Deg of coil rolling direction. So, when we test pipes in both directions, the long. samples will show higher values than in transverse direction.
Also, for Transverse samples, we need to flatten the sample and due to Bauschinger effect, there is significant drop in YS values and hence to take care of this phenomenon, the coils are designed at higher YS, so we can meet the min. properties in the finished pipe. As there is no flattening involved in Long. Tensile test, hence there is no effect of Bauschinger phenomenon. Because of these two attributes, the YS in Transvers direction vs YS in Long direction has a difference of around 10 Ksi. For YS-T to take care of 45 deg rolling direction values (which are lower than values in transverse direction) Bauschinger effect, properties variation at steel mills and pipes mills , The YS-T are required to be on the higher side in the coils to meet the specified min. YS in the pipes. As the values do not change much for Tensile strength, there is no significant difference in both the directions.

For HFW pipes- Transverse samples, we need to flatten the sample and due to Bauschinger effect, there is significant drop in YS values and hence to take care of all this, the coils are designed at higher YS, so we meet the min. properties. As there is no flattening involved in Long. Tensile test, so there is no effect of Bauschinger phenomenon. So because of these two attributes the YS in Transvers direction vs YS in Long direction has a big difference. As the values do not change much for Tensile strength, there is no significant difference in both the directions. Also, the YS change significantly with change in diameter. The drop in Transverse YS is higher in 20", 24" etc. where YS is more in pipe sizes like 10", 12" pipes.
To balance the properties in both directions, we need a higher range for YS in Long. Direction as the YS in Hoop stress direction is to be maintained so it withstands the field hydrotest pressure without any issues.
As detailed in cl. 4.1 of draft report- Although the terms undermatching and over matching can be applied to either the yield strength or tensile strength of the pipe material, it has become more common to base the degree of under/over match as a function of the pipe tensile strength, since in the limit (i.e., high applied strain)it is the pipe tensile strength which is more important.
Hence, as we know that Tensile strength is more important, the upper limit of 120 MPa (17.4 Ksi) should be applied only to Long. Tensile strength and not to Long. Yield Strength. This will help in keeping the YS-T values at a good level where there will be no issue of lower YS, Expansion during hydro test etc. By doing this, we can very well meet the Tensile Strength limits in long. direction with some values which may be out of these limits.

Also, it looks to be more problem of selection of welding process and consumables. With use of right selection of welding process and consumables, we can overcome this problem. As we have seen that all failures are contributed to SMAW process.

Date: 05/13/2020

Response on JIP “Enhanced Girth Weld Performance for Newly Constructed Grade X70 Pipelines”

Thank you for allowing Welspun the opportunity to provide feedback on this report. As mentioned in our previous emails, we don’t agree with the report and its recommendations. Welspun has supported this investigation to the fullest possible extent by providing valuable inputs and data .It is our opinion the nature of the failures may be related more to the quality of the weld/field joints than to the weld heat affected zone properties. As such, more focus would seem appropriate in controlling the quality of the field girth welds.

Here are few points:

1. Since this JIP is based on the failure of multiple field joints, the main focus of the JIP should have been the metallurgical failure analysis of such instances. After providing limited information about the failures, it is stated the welds were deemed as being “code compliant” . . This investigation is beyond code compliance as all the involved parties, including pipe mills and steel mills are complying with the codes. Any X70 project is beyond API code compliance and require special attention and detail that is beyond being code compliant.

2. Since the failures were only related to Spiral and HFW pipes, we are not sure recommending the same practices for LSAW pipe is warranted. There should be discussion in the report stating why there are no failures in LSAW pipes. The three processes are completely different from the stand point of steel making , plate/coil processing and pipe manufacture .

3. It appears a number of failure analyses indicate the girth weld quality to be an issue . Also there is no information covering the mechanical properties and processing history of the failed pipes. Although HAZ softening is mentioned as the root cause of the failure, it is evident that if higher heat inputs are used for welding , softening can occur. Additional to highlighting the pipe’s contribution to softening, the welding procedures need to be addressed as well .

4. Page# 43; chemical composition table is confusing. For example sample # 101229 is obviously chemical compositions of two different heats and grades and may represent two different casting campaigns. We haven’t seen such difference of chemical composition in the same campaign unless there are traceability issues. For the other three samples, we don’t consider there to be a major difference in the chemical composition. We can always find such difference in a casting campaign ; metallurgically it shouldn’t lead to any issues. It is stated that these minor variations may lead to HAZ softening; however no effort was made to prove that was the case .

5. In section 7.3.2, there is no discussion related to the control of girth weld quality. How were the girth weld made, how many welders performed the welding, what kind of heat inputs were used? Was any NDT test performed before performing the testing?

6. On longitudinal testing requirements: All the pipe mills are doing transverse testing and meeting API requirements . When customers request both transverse and longitudinal tests, we do the testing and try to be in the limits specified . It is well understood that pipe properties are , to a large extent , dependent on the coil/plate properties. For hot strip mill production the suppliers are testing the outer wrap (practically possible) of the coil before shipping . As such , there is no way of knowing what variation in mechanical properties might be seen after pipe manufacture . API provides a transverse yield strength range of 150 MPa for X70 ; which is consistent for the grades between X60M to X80M. As API doesn't have a requirement for longitudinal testing of HFW and Spiral pipes; bringing a tighter yield strength range requirement than the existing transverse range can be challenging. The reasons given in the report for pipe mills for not accepting the proposed limit may be true for a few pipe diameters and thickness but is not for all diameter size and thickness. In the report, it is mentioned that round bar tensile and ring expansion tests can be used to replace flattened reduced section specimen. First of all, round bar specimen do not include full wall thickness and therefore may not be a true representation of the mechanical properties . Also , the preparation of round bar specimens is time consuming and costly for projects with tight deadlines. Ring expansion testing can only provide yield strength results , thereby requiring additional tests be performed to document the tensile strength . We believe these tests may be good supplementary requirements but are not a replacement for flat specimen test.

7. Pipe mills are continuously working with welding consumable providers and providing them feedback in order to enhance the performance of the pipe weld seam. Welding consumable manufacturers can easily tweak the electrode composition to improve weld deposition and meet any enhanced property requirements . Generally, Lincoln Electric, ESAB and other manufacturers are always ready to collaborate and develop new products. From the report , it is not evident what kind of effort was made in this direction.

8. It is mentioned that for thinner wall pipelines, the use of lower grade pipelines should be considered to avoid the use of X70 . Obviously , we don't agree with this statement as we have produced more than 8000 miles of thin wall Grade X70 spiral weld pipe . To date not a single customer has approached us with any issue related to field welding or in service performance .

9. On HAZ softening- HAZ hardening or softening can occur based on the steel composition and welding conditions. HAZ softening cannot be attributed to steel composition, only . More analysis should have been conducted to understand the relationship between chemical composition and welding conditions that promote HAZ softening. Even though higher longitudinal tensile properties and lower HAZ hardness values were mentioned as the main causes , it was not demonstrated that these are the only two reasons that lead to the field girth weld failures noted in the report .There are numerous pipelines in service with properties similar to those reported as contributing to the field girth weld failures .
10. Given the results of the JIP there is no interest on the part of Welspun to support any further work as it pertains to field girth weld HAZ softening .

P. N. Mahida

Welspun Tubular LLC
9301 Frazier Pike, Little Rock, Arkansas 72206
O: +1 501 301- 8800 | F: +1 501 470-1759
www.welspunpipes.us.com | www.welspun.com