Background of Linepipe Specifications

Topical Report 277-T-01

For Project

Weld Design, Testing, and Assessment Procedures for High Strength Pipelines

Prepared for the
Design, Materials, and Construction Technical Committee of
Pipeline Research Council International, Inc.
Project MATH-1 Catalog No. L5XXXX

and

U.S. Department of Transportation
Pipeline and Hazardous Materials Safety Administration
Office of Pipeline Safety
Agreement Number DTPH56-07-T-000005

Prepared by
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November 28, 2011

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FINAL REPORT STRUCTURE

Focus Area 1 - Update of Weld Design, Testing, and Assessment Procedures for High Strength Pipelines		
Report #	**Description**	**Lead Authors**
277-T-01	Background of Linepipe Specifications	CRES/CANMET
277-T-02	Background of All-Weld Metal Tensile Test Protocol	CANMET/Lincoln
277-T-03	Development of Procedure for Low-Constraint Toughness Testing Using a Single-Specimen Technique	CANMET/CRES
277-T-04	Summary of Publications: Single-Edge Notched Tension SE(T) Tests	CANMET
277-T-05	Small Scale Tensile, Charpy V-Notch, and Fracture Toughness Tests	CANMET/NIST
277-T-06	Small Scale Low Constraint Fracture Toughness Test Results	CANMET/NIST
277-T-07	Small Scale Low Constraint Fracture Toughness Test Discussion and Analysis	CANMET/NIST
277-T-08	Summary of Mechanical Properties	CANMET
277-T-09	Curved Wide Plate Tests	NIST/CRES
277-T-10	Weld Strength Mismatch Requirements	CRES/CANMET
277-T-11	Curved Wide Plate Test Results and Transferability of Test Specimens	CRES/CANMET
277-S-01	Summary Report 277 Weld Design, Testing, and Assessment Procedures for High Strength Pipelines	CRES

Focus Area 2 - Development of Optimized Welding Solutions for X100 Linepipe Steel		
Report #	**Description**	**Lead Authors**
278-T-01	State of The Art Review	Lincoln
278-T-02	Material Selection, Welding and Weld Monitoring	Lincoln/CANMET
278-T-03	Microstructure and Hardness Characterization of Girth Welds	CANMET/Lincoln
278-T-04	Microstructure and Properties of Simulated Weld Metals	CANMET/Lincoln
278-T-05	Microstructure and Properties of Simulated Heat Affected Zones	CANMET/Lincoln
278-T-06	Essential Welding Variables	Lincoln/CANMET
278-T-07	Thermal Model for Welding Simulations	CRES/CANMET
278-T-08	Microstructure Model for Welding Simulations	CRES/CANMET
278-T-09	Application to Other Processes	Lincoln/CANMET
278-S-01	Summary Report 278 Development of Optimized Welding Solutions for X100 Line Pipe Steel	Lincoln

EXECUTIVE SUMMARY

Some of the future pipelines are expected to be constructed in remote areas. The environment in these areas can impose higher longitudinal plastic deformation on the pipelines. Such environmental conditions include, but not limited to, frost heave and thaw settlement in the northern arctic region, seismic activity, slope instability, mine subsidence, upheaval buckling, etc. The overall industry experience for this type of loading is very limited.

The other trend in new pipeline construction is the move towards higher internal pressure (design factor of 0.80 as opposed to the more traditional 0.72 for Class 1 designs) and the use of high strength linepipes (API 5L Grade X70 and higher). The ability to operate at high international pressure enhances the economic return of the pipelines and provides additional incentive to select high strength linepipes.

To ensure pipeline safety and integrity, it is necessary to examine linepipe specifications and new design concepts under the new material and loading conditions. The overall objective of this work is the development of requisite format for linepipe specifications for the new design concepts and the new pipeline environment, particularly for strain-based design. The necessary material characteristics that needs to be specified for these new conditions is highlighted.

This report covers the following elements:

1. Review of linepipe specifications in the current codes and standards,
2. Review of characteristic features of modern linepipes,
3. Examination of the potential influence of those features on the performance of the linepipes, particularly for strain-based designs, and
4. Recommendation of the format of linepipe specifications by considering the new design requirements and salient features of modern high strength linepipes.

The focus of this report is the mechanical properties of the linepipes and their influence on pipeline performance. The alloy design of steels, plate and coil rolling practice, and pipe manufacturing process can have profound effects on the resulting mechanical properties of the linepipes. The specifications of these manufacturing parameters leading to the final mechanical properties are out of the scope of this report.

The identified generic issues that are relevant to both traditional stress-based and new strain-based designs are (1) definition of yield strength, (2) test specimen form and dimensions, (3) test temperature, (4) effects of strain ageing, (5) reduction of allowable upper bound strength, (6) dimensional tolerance of linepipes, and (7) assurance of consistent test protocols and post-test data analysis procedures. For strain-based design, the additional considerations are associated with the longitudinal properties and the characterization of full stress-strain curves.

A few new trends in linepipe development are noted. The so-called "high-strain" pipes are produced specifically to increase the compressive strain capacity of pipes and the resistance to the effects of strain ageing. Certain features of these pipes, such as strain hardening capacity,

cannot be adequately characterized by traditional test methods and specifications, such as Y/T ratio. The proper characterization of the type of pipes should be examined.

The allowance of extremely high Y/T ratio for high strength linepipes, e.g., Y/T limit of 0.99 for X120, brings a new set of unknowns. Certain stress-based design and maintenance criteria, such as corrosion assessment tools and ductile fracture initiation criteria, have certain implicit assumptions about material's strain hardening capacity. The applicability of those criteria in the context of very high Y/T ratios is unknown and should be critically evaluated. Furthermore, pipelines designed by traditional stress-based principles may still experience certain displacement-controlled loading after the pipelines are put in service. Any potential use of very high Y/T materials changes the implicit safety factors that the industry has had a successful experience.

Some features of longitudinal tensile properties, such as Y/T ratio, are often viewed as more important in strain-based design than those of hoop properties. In should be recognized that the principles of stress-based design should be applied for pressure containment even when the pipelines are subjected to high longitudinal strains. For in-service pipelines, the sequence of pressure loading and longitudinal straining can change over time and there could be multiple loading cycles. Both hoop and longitudinal properties can have influence on the overall integrity of the pipelines. Furthermore the effects of anisotropy in tensile properties on the pipeline integrity should be examined.

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1 INTRODUCTION

1.1 INCENTIVE

High strength pipelines offer many advantages over their lower strength counterparts for long distance transportation of natural gas and liquid energy products. Some of these benefits include, but not limited to, reduced material cost, faster construction speed from reduced welding time, and reduced transportation cost. The other trend in the new natural gas pipeline projects is the move towards higher internal pressure (design factor of 0.80 as opposed to the more traditional 0.72 for Class 1 designs). The ability to operate at high internal pressure enhances the economic return of the pipelines and provides additional incentive to select high strength linepipes.

As pipelines are being constructed in remote areas, the environment can cause longitudinal plastic deformation in the pipelines beyond the strain range of the vast majority of the existing pipelines. Such environmental conditions include, but not limited to, frost heave and thaw settlement in the northern arctic region, seismic activity, slope instability, mine subsidence, upheaval buckling, etc. The overall industry experience for this type of loading is very limited.

To ensure pipeline safety and integrity, it is necessary to examine linepipe specifications and new design concepts under the new material and loading conditions, i.e., the trend towards higher strength linepipes and more demanding environment than those existed for traditional pipelines.

1.2 OBJECTIVE

The overall objective of this work is the development of requisite format for linepipe specifications for the new design concepts and the new pipeline environment, particularly for strain-based design. The necessary material characteristics that needs to be specified for these new conditions is highlighted. Test methods by which the characteristics can be reliably and consistently characterized are provided.

1.3 SCOPE OF THIS REPORT

To achieve the objectives stated above, this report consists of the following key components:

1. Review of linepipe specifications in the current codes and standards,
2. Review of characteristic features of modern linepipes,
3. Examination of the potential influence of those features on the performance of the linepipes, particularly for strain-based designs, and
4. Recommendation of the format of linepipe specifications by considering the new design requirements and salient features of modern high strength linepipes.

The focus of this report is the mechanical properties of the linepipes and their influence on pipeline performance. The alloy design of steels, plate and coil rolling practice, and pipe manufacturing process can have profound effects on the resulting mechanical properties of the linepipes. The specifications of these manufacturing parameters leading to the final mechanical properties are out of the scope of this report.

2 LINEPIPE TENSILE SPECIFICATIONS IN CURRENT CODES AND STANDARDS

Traditional pipeline design targets the pressure containment by limiting the hoop stress to certain percentage of SMYS. Consequently the focus of the linepipe tensile tests is the hoop property. For large diameter welded pipes, the required tests related to tensile properties are tensile tests in the hoop direction of the pipe body and cross seam-weld tensile tests [1,2].

2.1 SPECIFICATIONS BY PSL

API 5L 44th Edition [1] and ISO 3183 [2] have two product specification levels (PSL) for linepipes. Level PSL 1 provides a standard quality level for linepipe grades up to X70. The specified properties are minimum yield strength, minimum ultimate tensile strength (UTS) and minimum elongation for the pipe body tests. Level PSL 2 adds mandatory requirements for the maximum yield strength, maximum UTS, and maximum Y/T ratio for linepipe grade up to X120.

2.2 TEST SPECIMEN ORIENTATION

The orientation of tensile test specimen depends on pipe diameter. For welded pipe with specified outside diameter (OD) less than 219.1 mm (8.625”), the specimens are taken in the longitudinal direction of the pipe. Specimens in transverse direction are taken for pipes of larger diameter. The orientation of specimen for different PSL 2 pipes of various diameters is shown in Table 1 and Figure1.

2.3 FORM AND DIMENSION OF TEST SPECIMEN

The form of test specimen can be either flattened full-thickness rectangular strap or round bars from non-flattened pieces. The gauge diameter of test specimens is given as a function of pipe diameter and wall thickness in Table 1 of ISO 3183 [2]. For welded pipe with specified outside diameter (OD) less than 219.1 mm (8.625”), full-section longitudinal test specimen may be used. Ring expansion specimens may be used to substitute transverse specimens to determine the yield strength. The location of tensile test specimen for pipe body properties should be sufficiently far away from seam welds.

2.4 YIELD STRENGTH DEFINITION

The yield strength of linepipe is determined at 0.5% total strain for pipe grade equal or less than X90 and 0.2% offset strain for pipe grades higher than X90. The tests are performed in accordance with ASTM A370 or ISO 6892.

Table 1. Number, orientation and location of tensile specimen for PSL 2 pipes

Type of Pipe	Specified Outside Diameter: mm (inch)			
	< 219.1 (8.625)	219.1 (8.625) to 323.9 (12.75)	323.9 (12.75) to 508.0 (20.0)	≥ 508.0 (20.0)
SMLS, not cold-expanded	1L[a]	1L[b,c]	1L[b,c]	1L[b,c]
SMLS, cold-expanded	1L[a]	1T[c]	1T[c]	1T[c]
HFW	1L90[a]	1T180[c]	1T180[c]	1T180[c]
SAWL or COWL	1L90[a]	1T180[c]	1T180[c]	1T180[c]
SAWH or COWH	1L[a]	1T[c]	1T[c]	1T[c]

[a] Full section longitudinal test specimen may be used at the option of manufacturer.

[b] If agreed, transverse test specimen may be used.

[c] If agreed, annular test specimen may be used for the determination of transverse yield strength by the hydraulic ring expansion test in accordance with ASTM A370.

SMLS Seamless pipe
HFW High-frequency electric welding process
SAWL Submerged-arc longitudinal welding process
SAWH Submerged-arc helical welding process
COWL Combined (gas metal arc and submerged arc) longitudinal welding process
COWH Combined (gas metal arc and submerged arc) helical welding process

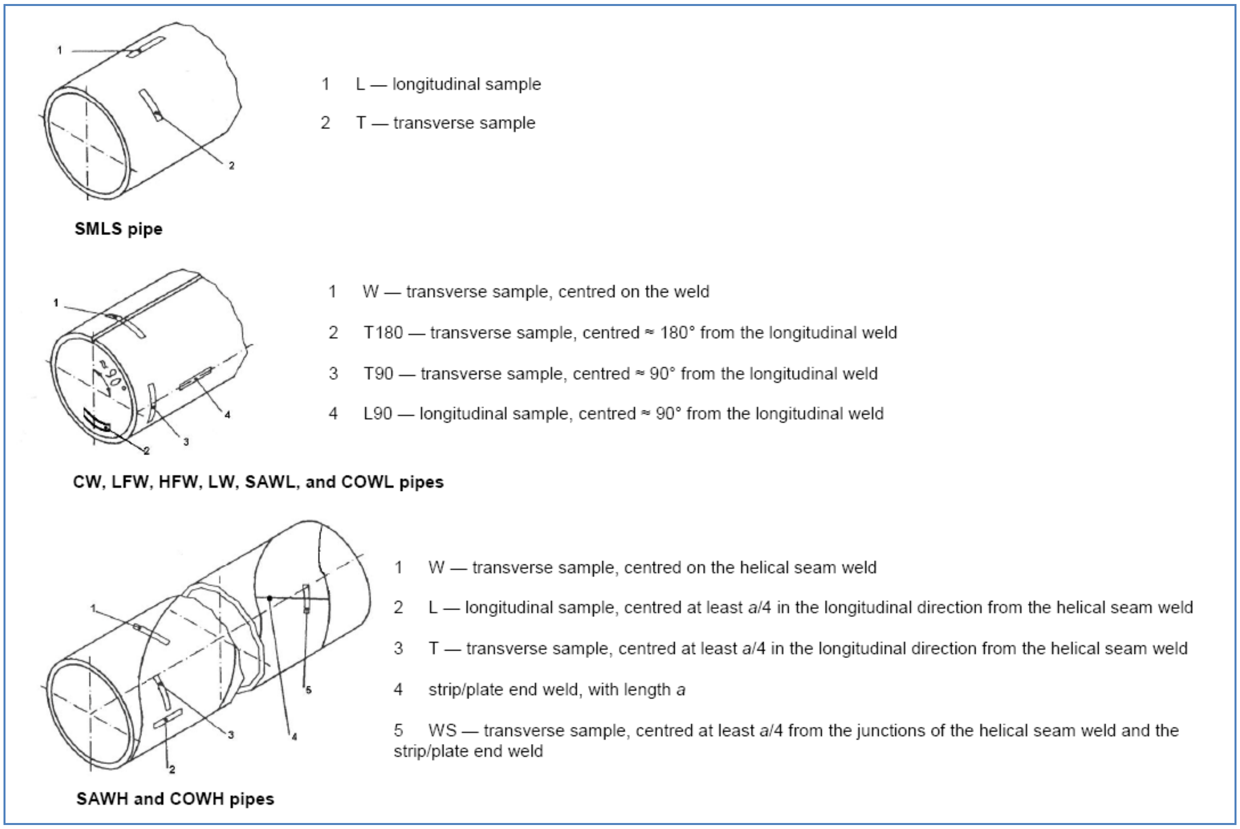


Figure 1. Location and orientation of tensile test specimens [1]

2.5 UPPER LIMITS OF YIELD STRENGTH, UTS AND Y/T RATIO

The upper limits of yield strength and UTS are listed in Table 2 [1,2]. It can be seen that the maximum yield strength is about 150 MPa higher than the specified minimum yield strength (SMYS) for X80-X100. For X120, the maximum yield strength is about 220 MPa higher than the SMYS. The maximum UTS is about 200 MPa and 220 MP higher than the specified minimum UTS for X80 and X90, respectively. For X100 and X120, the maximum UTS is 230 MPa higher than the specified minimum UTS.

The maximum Y/T ratios for different grades are listed in Table 2. The maximum permissible Y/T ratios of X100 and X120 are particularly high. The significance of those high Y/T ratios is discussed in Section 4.4.

Table 2. Number, orientation and location of tensile specimen for PSL 2 pipes

Pipe Grade	Yield Strength				Tensile Strength				Y/T
	Minimum		Maximum		Minimum		Maximum		Maximum
	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	
X80	555	80.5	705	102.3	625	90.6	825	119.7	0.93
X90	625	90.6	775	112.4	695	100.8	915	132.7	0.95
X100	690	100.1	840	121.8	760	110.2	990	143.6	0.97*
X120	830	120.4	1050	152.3	915	132.7	1145	166.1	0.99*

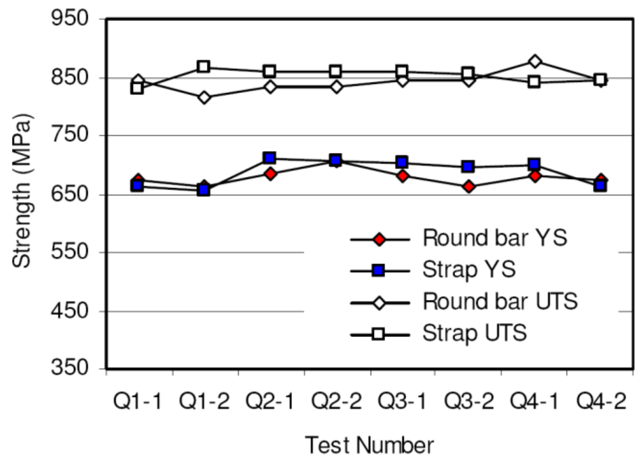
*Lower Y/T ratio may be specified by agreement for X100 and X120 pipes.

3 FEATURES OF MODERN HIGH-STRENGTH LINEPIPES

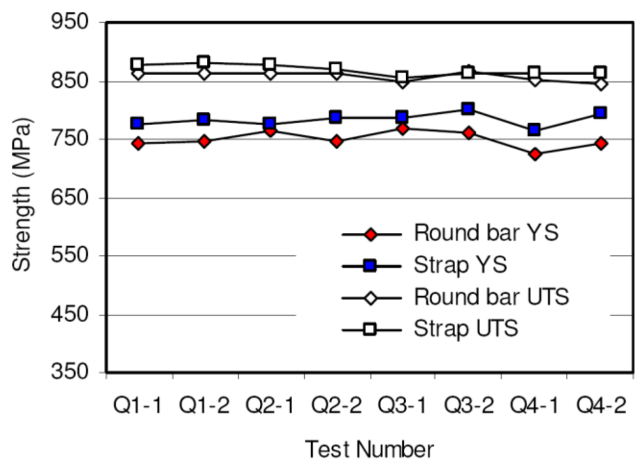
3.1 DEPENDENCE ON SPECIMEN GEOMETRY

3.1.1 Longitudinal Tensile Property

The longitudinal tensile properties were studied by Bai, et al. [3] and Klain, et al. [4] in non-aged and aged conditions. In the non-aged condition, the full-thickness straps and round-bar specimens give similar results as shown in Figure 2(a). In aged condition, both specimen forms give similar UTS values as shown in Figure 2(b). The yield strength in full-thickness strap is higher than that of round-bar specimens. Overall there is a slight rise in UTS from non-aged to aged condition. There is a large increase in the yield strength from non-aged to aged condition.



(a) LPA tensile test in the hydrotested condition



(b) LPA tensile tests in the aged condition

Figure 2. Effect of specimen geometry and strain aging on longitudinal pipe axis (LPA) tensile results [4]

The diameter of the round bar specimens may affect the test results. Specimens of larger diameter typically produce higher strength because they contain more fine-structured material near the pipe surfaces. Therefore, if round-bar specimens are used, the diameter should be as large as possible to capture the full-thickness properties.

The stress-strain curves from the round bar and rectangular cross-section strap are compared in Figure 3 from tests within this project. There are some differences between the curves of different specimen types. Both types of specimens produced similar results up to UTS. The total elongation from the strap specimens is much higher than that from the round bar specimens. The difference is attributable to the different specimen cross-section (round versus rectangular) and the ratio of gage width (diameter) to gage length. Both types of specimen had the same gage length of 2 inches while the cross-sectional areas were different. These results show that the specification for the total elongation has to be defined in the context of the specimen type and dimensions.

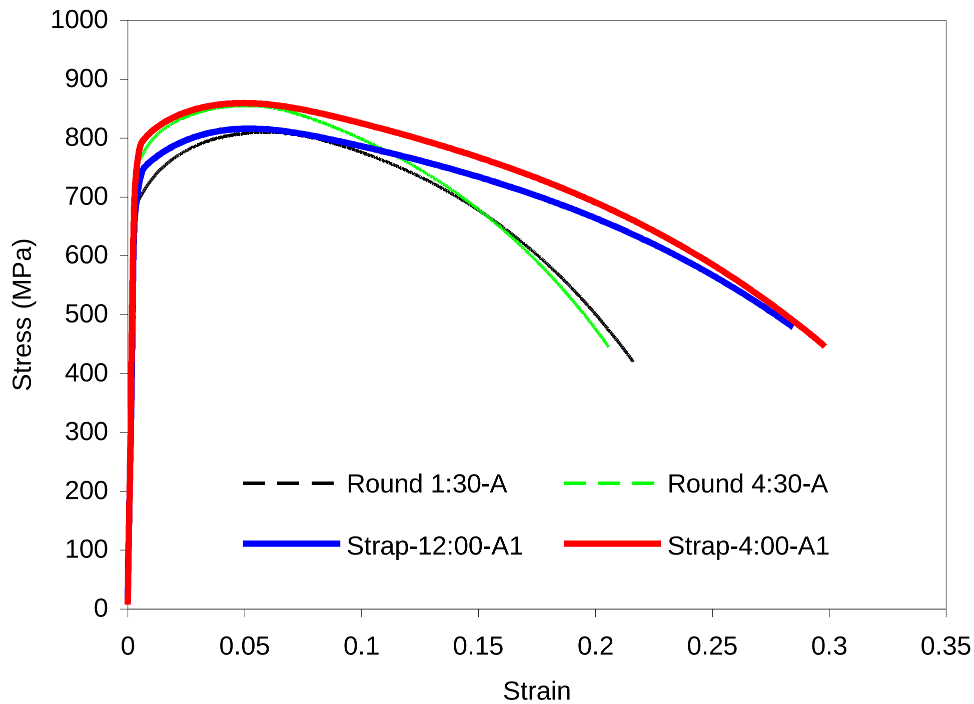


Figure 3. Comparison of stress-strain curves between the round bar and square cross-section strap

3.1.2 Transverse Tensile Property

Flatten straps are the nominal specimen form for transverse strength tests of large diameter pipes, while round bar and ring expansion are optional test forms. Studies have shown that the flattened straps can significantly underestimate the actual yield strength of pipe due to Bauschinger effects. Figure 4 shows that at increasing strength levels (above Grade 550 or X80), flattened straps significantly underestimated the actual yield strength of pipe [5].

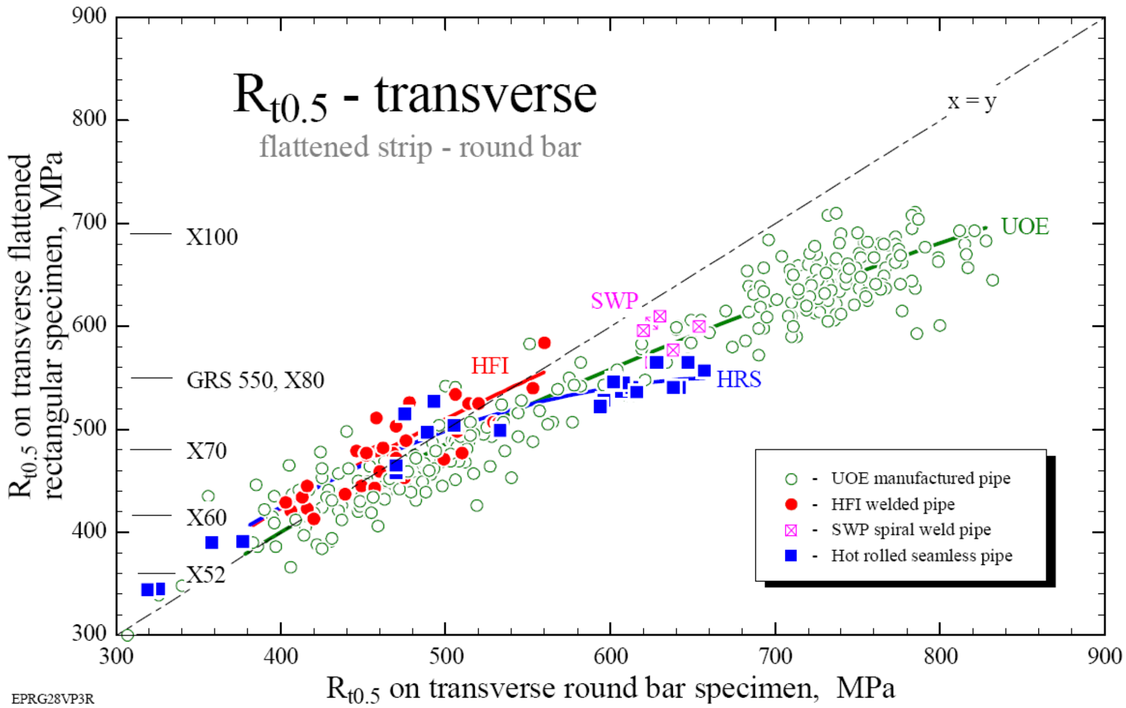


Figure 4. Comparison of yield strengths as measured by flattened strap and round bar for different types of pipes [5]

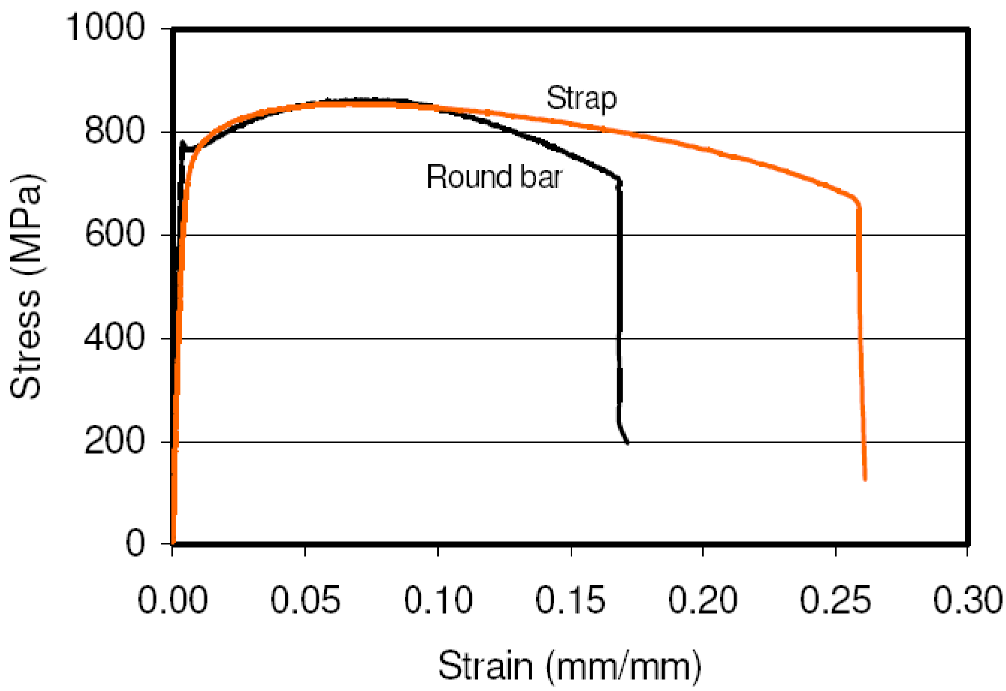


Figure 5. Stress-strain curves of strap and round bar specimens tested after strain aging process [4]

Round bars are shown to produce yield strength close to the actual transverse yield strength of the pipes [4,6]. In addition to producing lower yield strength, flatten strap specimens may give a reduced extent of Lüder's extension as shown in Figure 5 [4].

A series of ring expansion tests were performed to verify the results of round bar specimens [7,8]. The test results from a series of Grade 690 test samples of a number of pipe steel suppliers are summarized in Table 3 [7]. The test results confirmed that the yield strength from round bar specimens gave an accurate representation of the pipe's yield strength.

Liessem, et al., found that the results from ring expansion tests show reduced degree of Lüder's extension than those of round bar specimens as shown in Figure 6 [9]. It was suggested that the multi-axial stress state in ring expansion tests caused the reduced Lüder's extension.

Table 3. Comparison of round bar and ring expansion Tests [7]

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

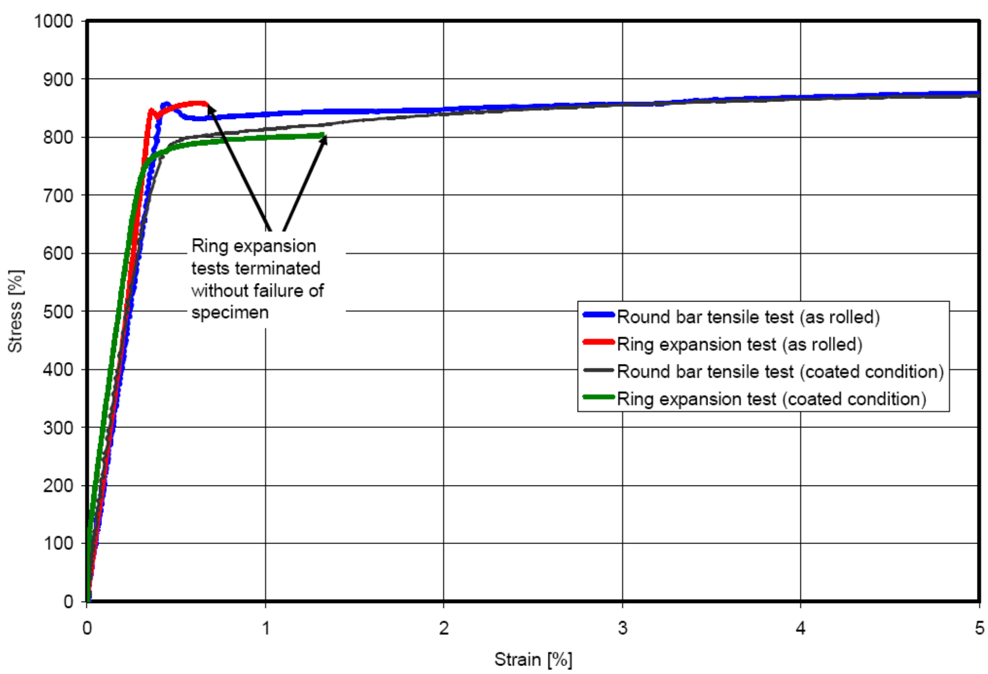


Figure 6. Stress-strain curves obtained from round bar tensile test and ring expansion tests [9]

3.2 ANISOTROPY

Modern high strength TMCP (thermal-mechanically controlled process) linepipe steels can have highly anisotropic mechanical properties (different stress-strain curves in longitudinal and transverse directions) due to the textures created in the plate/coil rolling process and the deformation introduced by the pipe forming and expansion processes (e.g., UOE).

The appearance of anisotropy in various linepipes could be different, as shown in Figure 7 and Figure 8. For one X100 linepipe, the UTS in the longitudinal and transverse directions, as measured by round bar specimens, is the same as shown in Figure 7 [10]. The yield strength in the transverse direction is, however, much higher than that in the longitudinal direction. The longitudinal stress-strain curve exhibits a clear "round-house" shape, while the transverse stress-strain curve has a much sharper turn between the elastic and plastic portion of the curve. The stress-strain curves of an early 2000's vintage X100 linepipe steel show that the yield strength and UTS in the transverse and longitudinal directions are quite different, see Figure 8 [11]. Similar to the stress-strain curves of Figure 7, the transverse curve shows a sharp yield point, whereas the longitudinal curve has the "round-house" shape. The difference in the yield strength between hoop and longitudinal directions can be significant, as shown in Table 4 from a recent TransCanada project [7].

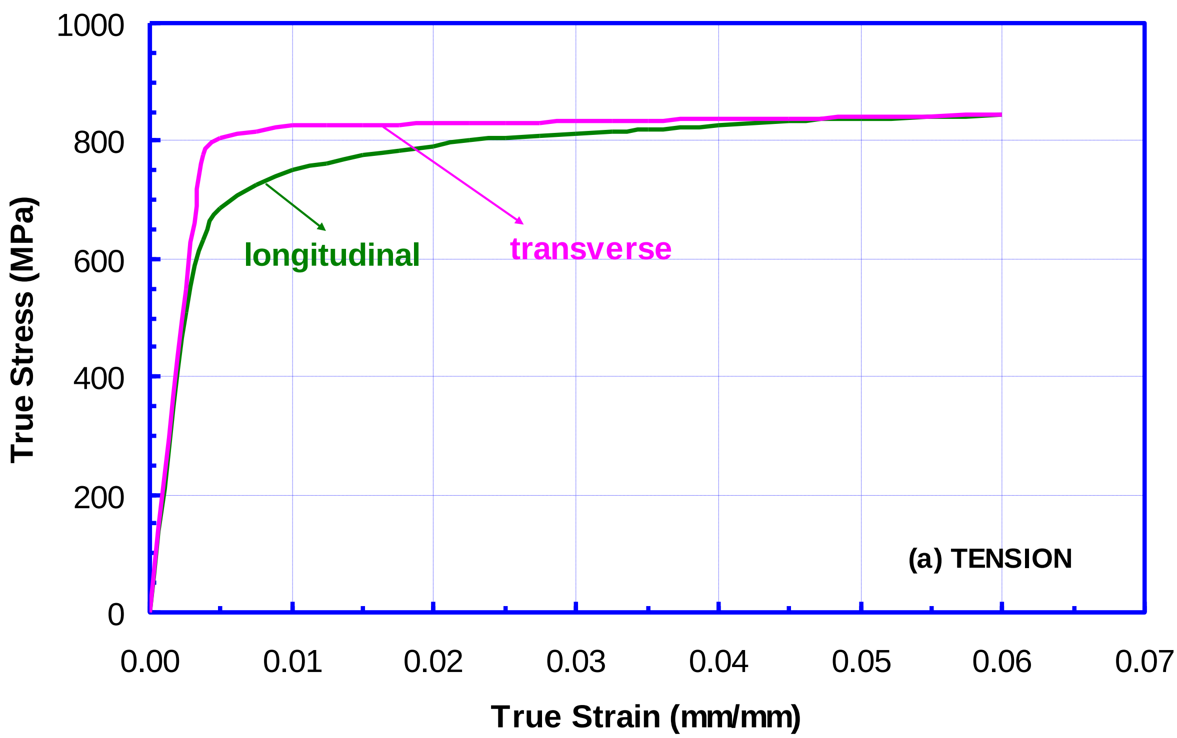


Figure 7. Stress-strain curves of an X100 linepipe tested in longitudinal and transverse directions showing anisotropy

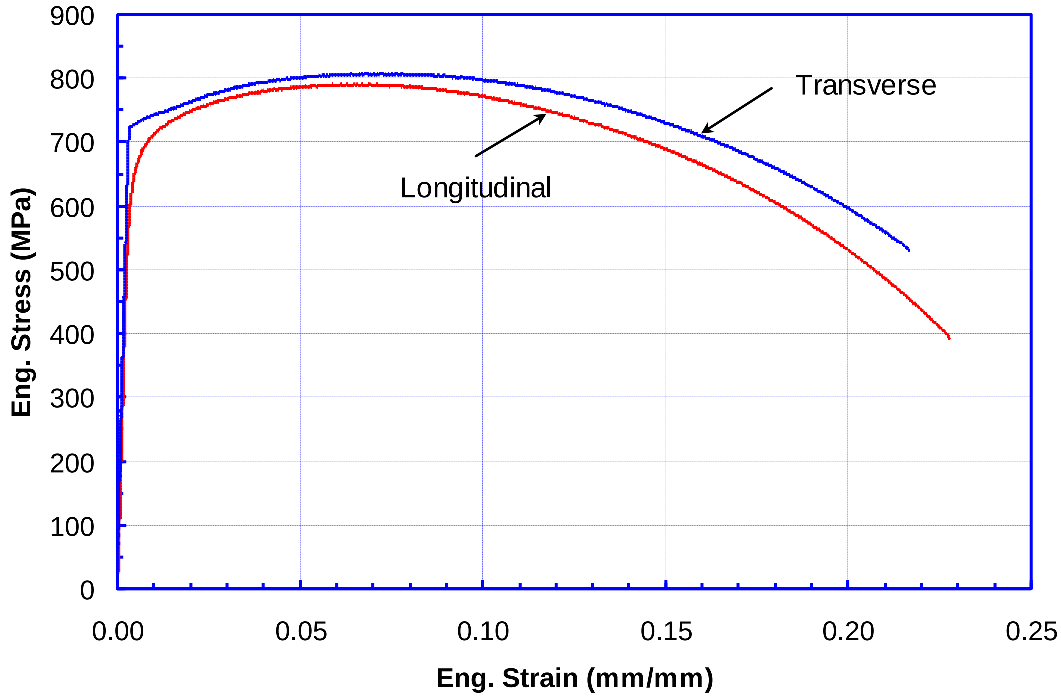


Figure 8. Longitudinal and transverse (hoop) stress-strain curves of an X100 linepipe of early 2000's vintage

Table 4. Comparison of transverse and longitudinal properties (round bar) for Grade 690 (X100) pipe [7]

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

3.3 DEFINITION OF YIELD STRENGTH

In pipeline design, the specified minimum yield strength, or SMYS, is probably the most fundamental material property. Figure 9 shows the stress-strain curves of two X100 linepipes from two manufacturers measured in longitudinal direction in full-thickness straps and one X80 linepipe for reference [12]. The X100 from Manufacturer 1 has a yield of 740 MPa (107.3 ksi) and UTS of 772 MPa (112.0 ksi), which gives a Y/T ratio of 0.96. The X100 from Manufacturer 2 has a yield of 640 MPa (92.8 ksi) and UTS of 819 MPa (118.8 ksi), which gives a Y/T ratio of 0.78. For the linepipe from Manufacturer 2, the yield strength measured at 0.5% total strain does not reflect the yield strength of the X100 linepipes as the 0.5% strain is less than the strain corresponding to the "knee" of the stress-strain curve. In a fundamental physics sense, the yield is associated with the plastic flow of a material. Such plastic flow is characterized by a small rise in the resistance to the applied stress when the applied strain is increased. For the X80 reference material in Figure 9, the 0.5% total strain definition of yield sufficiently captures the start of the plastic flow as the 0.5% strain corresponds to a point past the "knee" of the curve. For the X100 linepipe from Manufacturer 2, the 0.5% total strain line intercepts the stress-strain curves on the nominally elastic part of the stress strain response. Therefore the strength corresponding to this strain is not the physical yield strength.

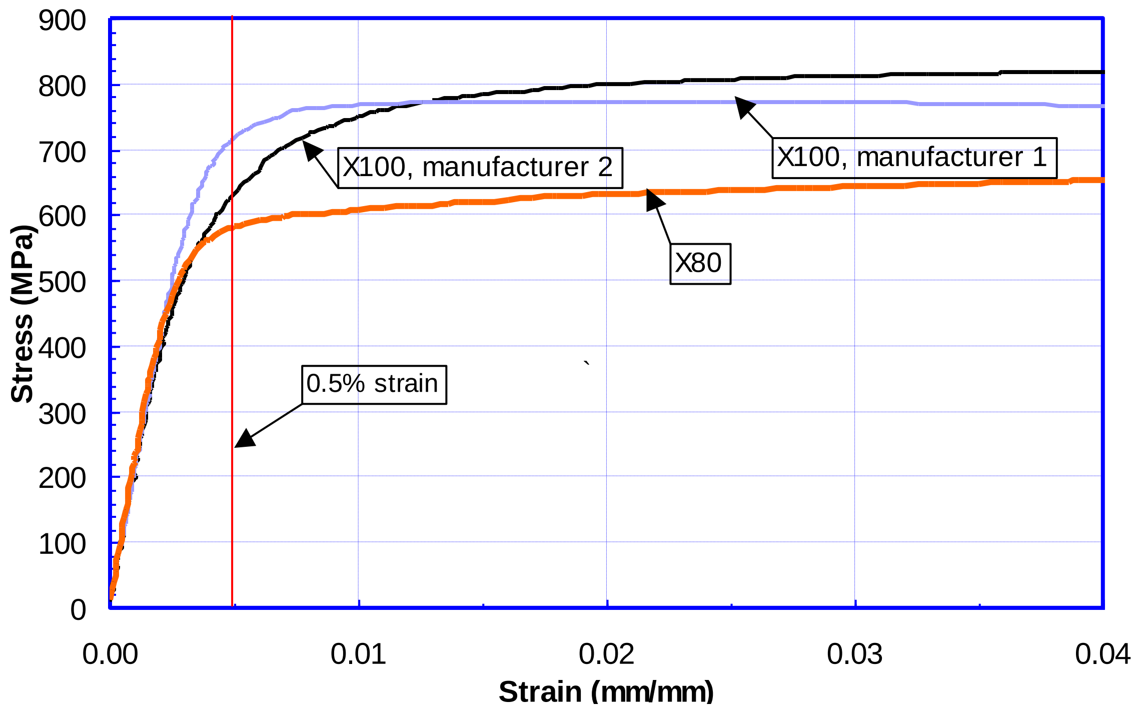


Figure 9. Stress-strain curves of two X100 linepipes and one X80 linepipe measured in full-thickness longitudinal straps

The issue with low reported yield strength can become even more pronounced with the so-called "high-strain" pipes. The longitudinal stress strain curves of those materials can have a gradual transition from elastic to the plastic part of the stress-strain curve. In addition, these materials are manufactured to resist strain aging during pipe coating [13,14,15]. A representative stress-strain curve is shown in Figure 10 [13]. When the yield strength is measured at either 0.5% total strain or 0.2% offset strain, the reported yield strength, as given in Figure 10 and Table 5, is much lower than the "physical" yield strength, which may be understood as the "knee" of the stress-strain curve. The reported low yield strength directly leads to the reported low *Y*/*T* ratio.

Klein, et al., [4] compared the 0.5% total strain and 0.2% offset strain definition of the yield strength of different grades of pipes as shown in Figure 11. As expected the yield strength from the 0.2% offset definition became higher than that of 0.5% total strain definition with the increase of the overall material strength. It should be noted that the elastic part of the stress-strain curves of Figure 11 is nearly linear. Consequently the yield strength values determined by either the 0.5% total strain or 0.2% offset strain definition, although different, may be viewed as representative of the material's yield strength. In contrast, the strength values reported in Table 5 cannot be viewed as representative of material's yield strength. The under-representation in the yield strength is attributable to the nonlinearity in the elastic part of the stress-strain curve and its interaction with the current definition of yield strength. For this type of materials, using

0.2% offset strain can produce similar under-representation of the yield strength as the 0.5% total strain.

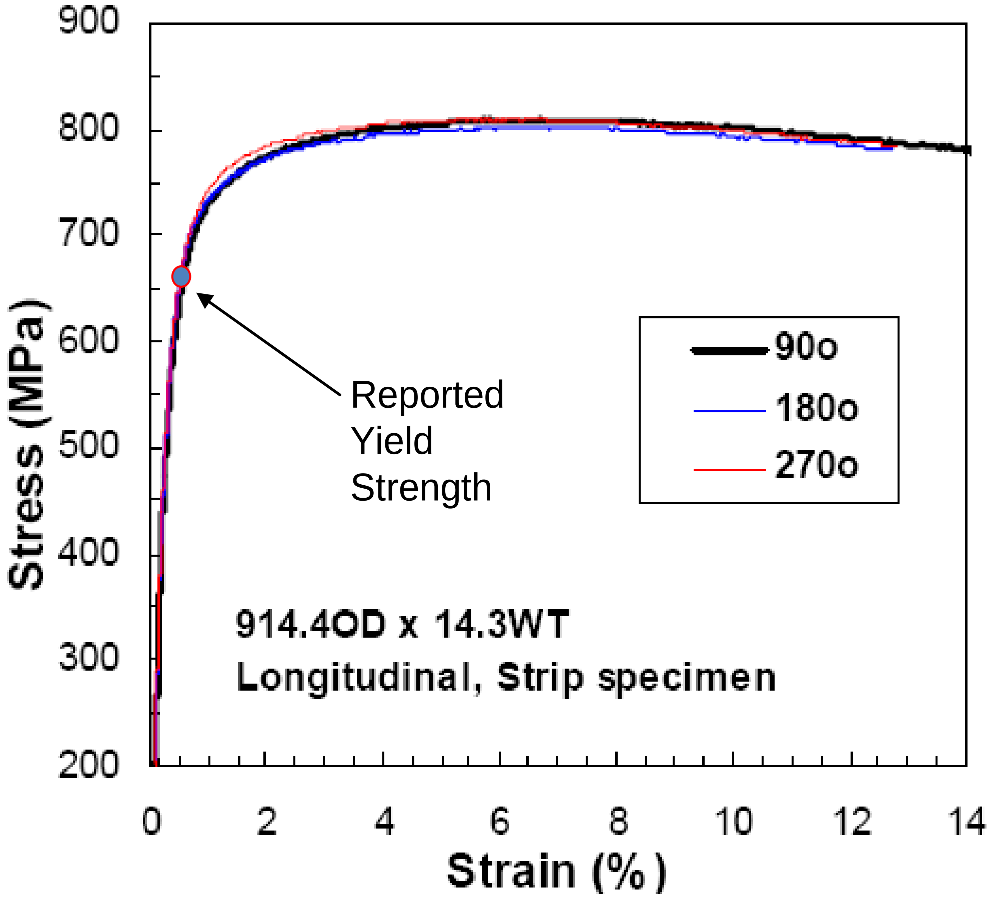


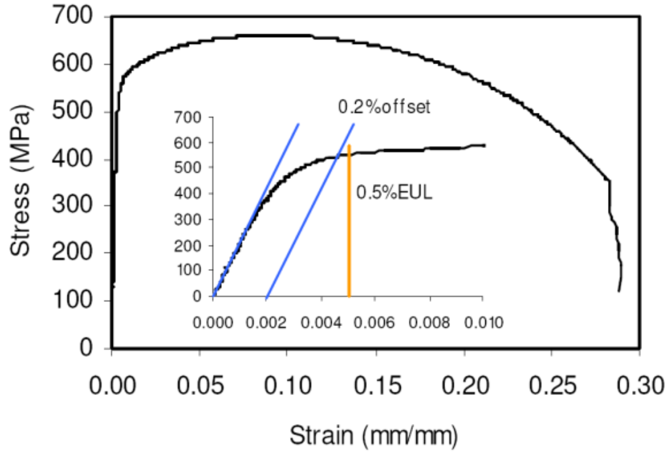
Figure 10. Stress-strain curves of a high-strain pipe and the associated yield strength by current codes [13]

Table 5. Reported strength values by current codes [13]

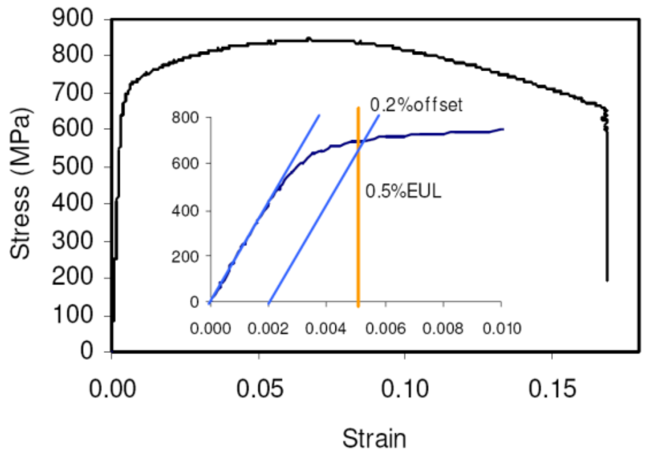
Pipe No.	Direction	Base metal tensile properties *1					Trans weld
		YS (MPa)	TS (MPa)	Y/T (%)	uEl (%)	σ_r *2 $\sigma_{1.5}/\sigma_{0.5}$	TS (MPa)
A	Trans.	713	824	87	-	-	819
	Longi.	668	835	80	7.3	1.17	-
B	Trans.	713	836	85	-	-	825
	Longi.	659	811	81	6.9	1.18	-

*1 Trans: round bar specimen, Longi.: Rectangular strip specimen

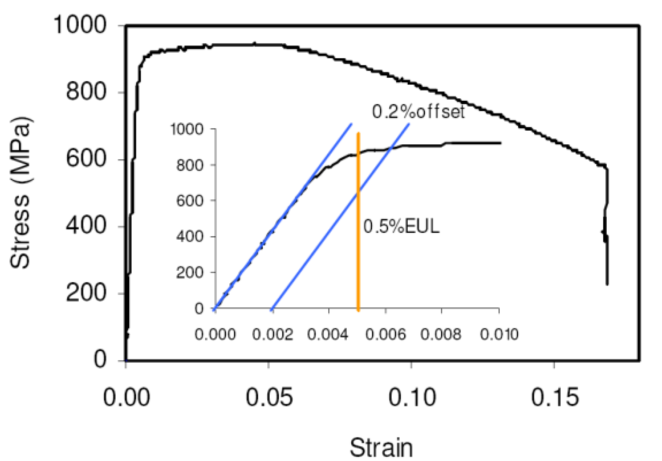
*2 Stress ratio, defined by the ratio of stress at ε=1.5% to that at ε=0.5% (σ1.5/σ0.5)



(a) Grade 550



(b) Grade 690



(c) Grade 825

Figure 11. Comparison of the yield strength by two different definitions

3.4 VARIATION OF TENSILE STRENGTH IN THE SAME PIPE

The need for weld strength overmatch for strain-based design requires a tight control of the spread (standard deviation) of pipe tensile properties. At the same time, any specifications aimed at achieving such tight control need to incorporate the natural variation of pipe tensile properties in the normal production environment. The room-temperature stress-strain curves from round and strap specimens cut from different clock positions are shown in Figures 12 and 13, respectively. The variation in yield strength is in the range of 80-90 MPa. This variation is higher than the estimated yield strength variation of 50-60 MPa (at 0.5% total strain) from published data by Tsuru, et al. [16]. The data published by Ishikawa, et al., seem to suggest much smaller variation [17].

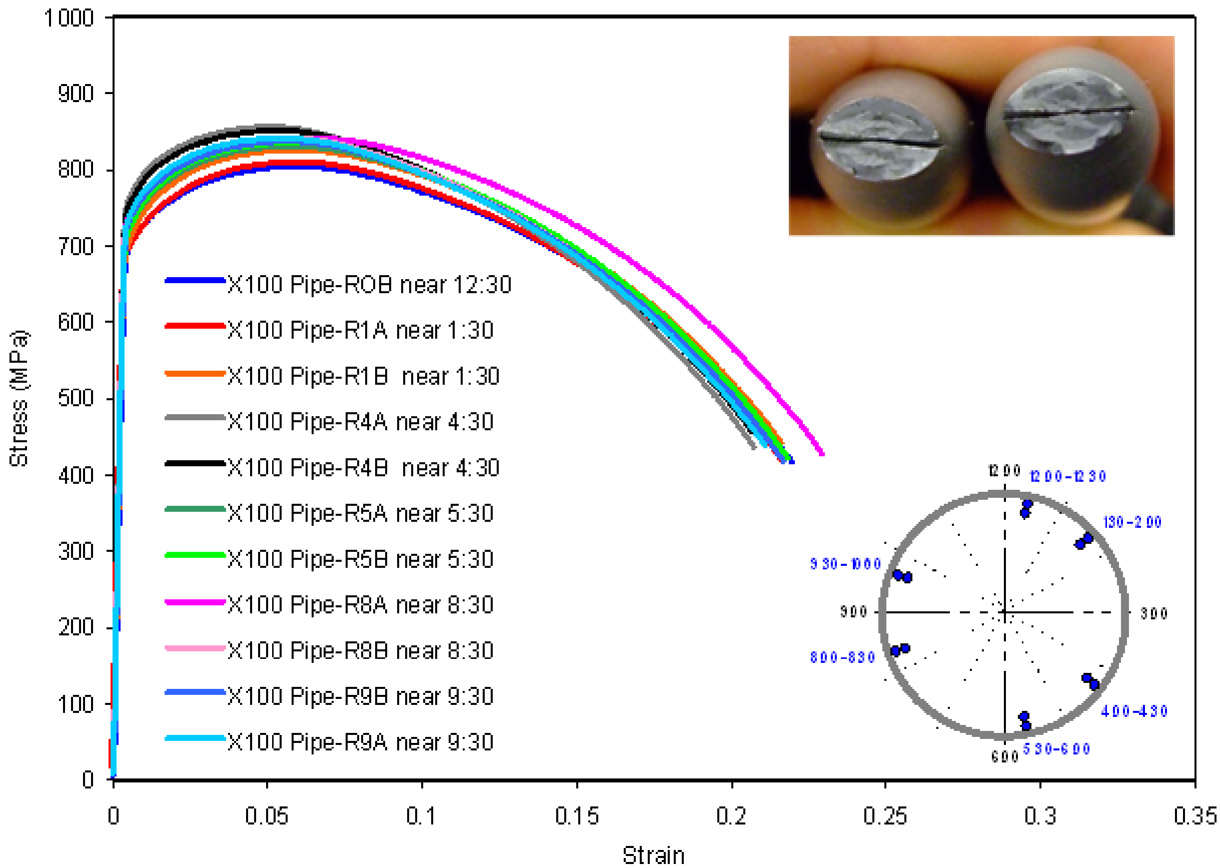


Figure 12. Stress-strain curves for tests using large diameter round specimens cut longitudinal to the pipe axis (LPA) at the different clock positions. Insert: image of fracture surfaces

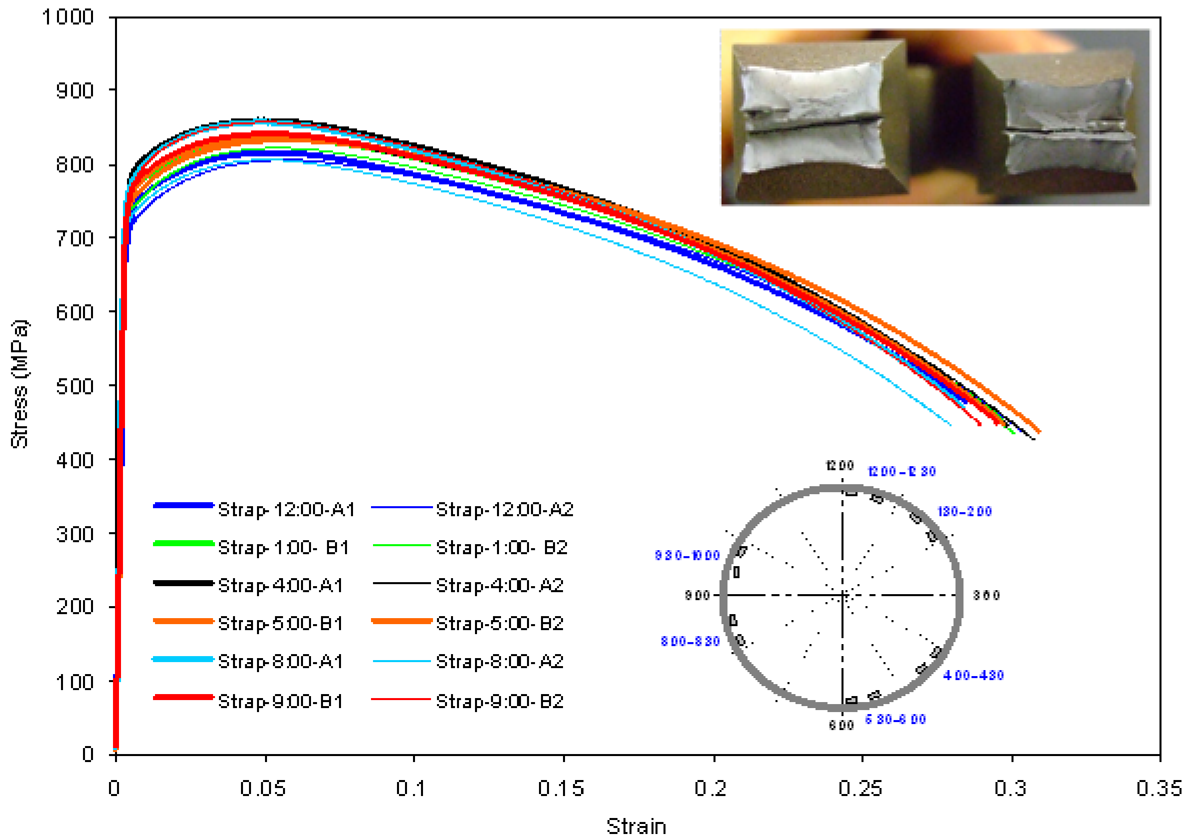


Figure 13. Stress-strain curves for tests using square strap tensile specimens cut longitudinal to the pipe axis (LPA) at different clock positions. Insert: image of fracture surfaces

3.5 DEPENDENCE ON TEST TEMPERATURE

Pipe tensile properties are in most cases obtained from room temperature tests. Past tests done on modern X70 and X100 pipe steels indicated that the increase in ultimate tensile strength (UTS) at lower test temperatures is greater than the increase of the yield strength, resulting in enhanced strain hardening behavior at low temperatures. The change in the tensile behavior, particularly the strain hardening capacity, is important for understanding the tensile strain capacity. The hoop tensile properties of an X70 pipe are compared in Figure 14 [18]. There is a marked increase in both strength and strain hardening capacity at -20ºC, consistent with prior observations. Similar trend is observed in the X56 pipes as shown in Figure 15.

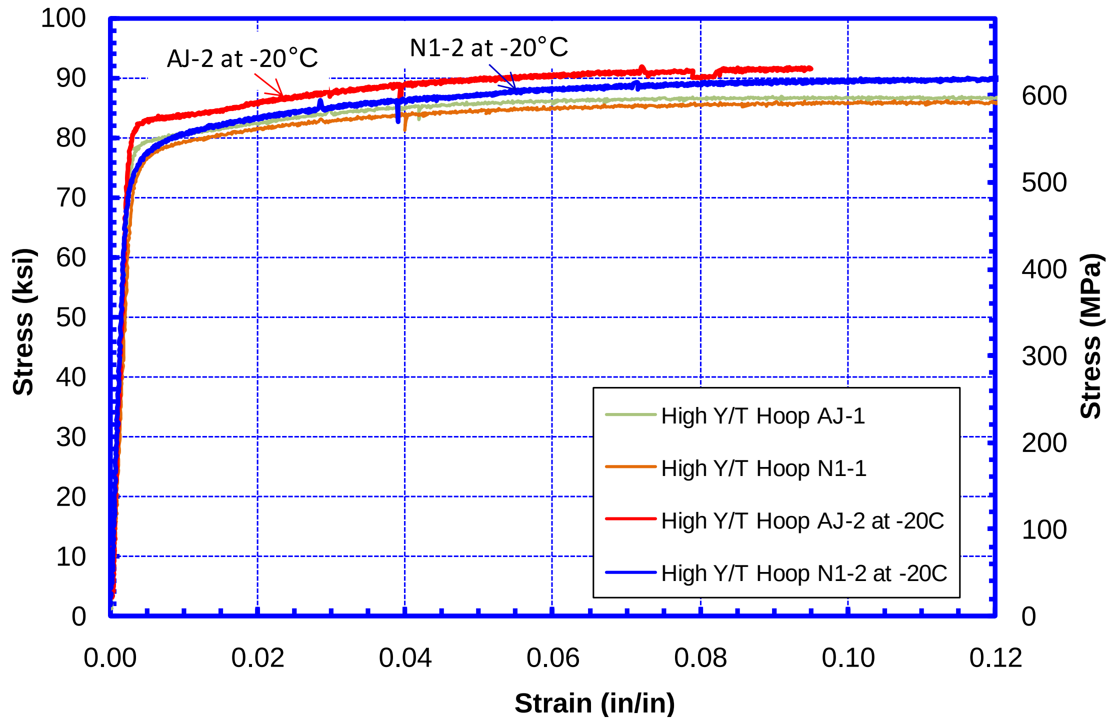


Figure 14. Hoop tensile property of an X70 pipe at room temperature and -20ºC [18]

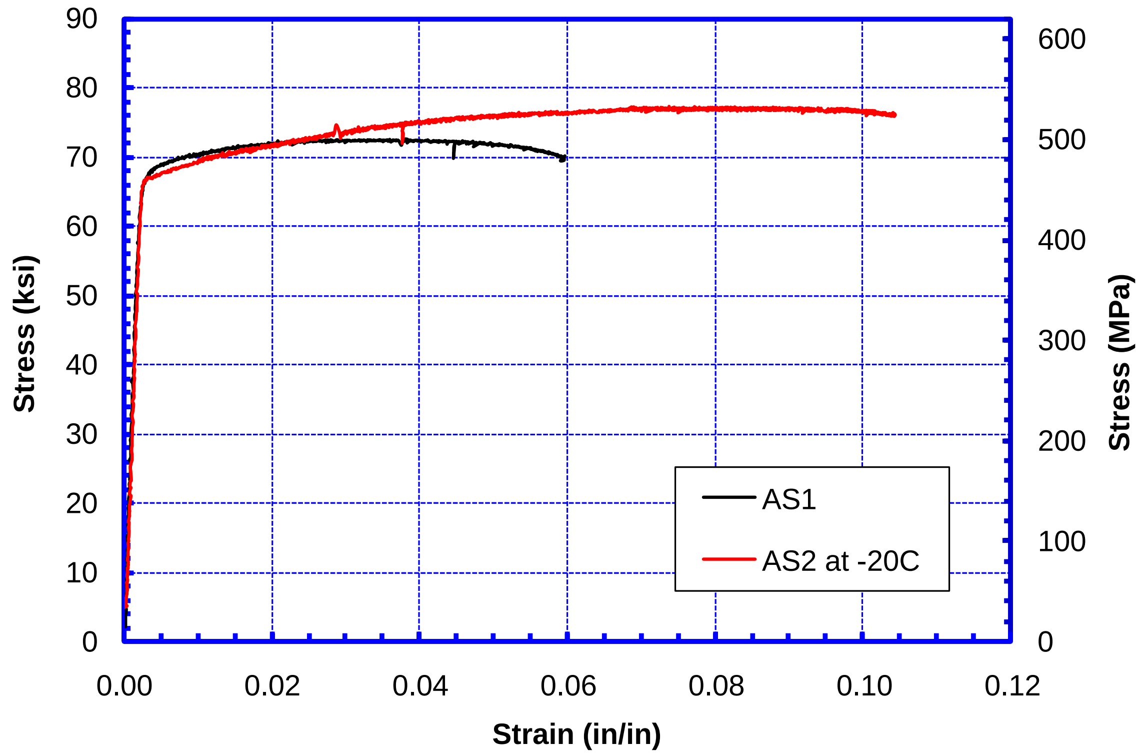
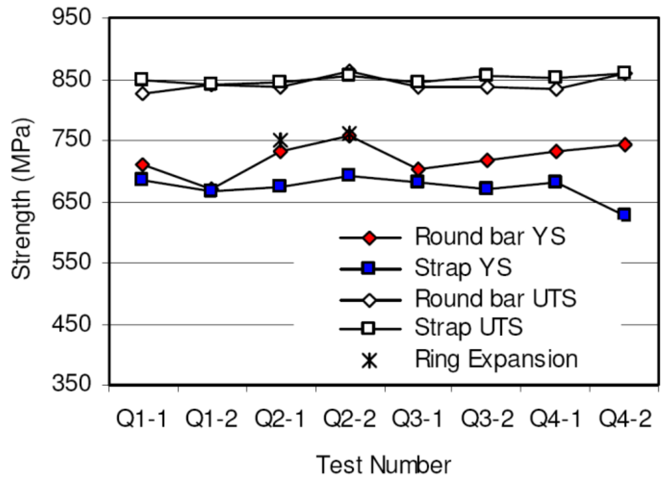


Figure 15. Hoop tensile stress-strain curves of an X56 pipe at room temperature and -20ºC [18]

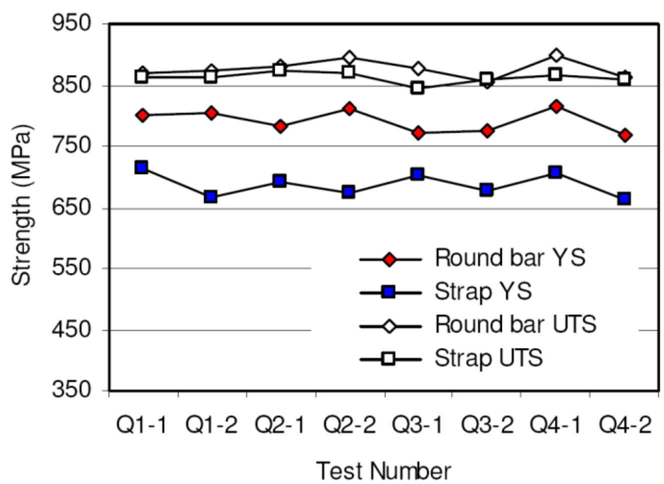
3.6 THE EFFECT OF STRAIN AGING ON LINEPIPE MECHANICAL PROPERTIES

3.6.1 Effect of Strain Aging on Tensile Properties

Various studies have shown that the strain aging can significantly increase the pipe yield strength (up to 100~160 MPa) in both longitudinal and transverse direction, while it has little effect on UTS [4, 19,15]. An example is shown in Figure 16 [4], in which the thermal aging was done at 240°C to simulate the pipe anti-corrosion coating process. The anti-corrosion FBE coating is normally applied at 200~250°C for several minutes after the pipe cold expansion process (in the case of UOE pipes). Because the strain aging increases pipe yield strength while it has little effect on the UTS, it can affect the Y/T ratio and weld strength mismatch level (if the mismatch level is measured by the yield strength). Both Y/T ratio and weld strength mismatch are critical parameters in strain-based design.



(a) TPA tensile tests in the hydrotested condition



(b) TPA tensile tests in the aged condition (at 240 °C)

Figure 16. Effect of strain aging (240°C) on transverse pipe axis (TPA) tensile strength of X100 pipe (6.35 mm round bar) [4]

3.6.2 Effect of Strain Aging on the Shape of Stress-Strain Curves

Strain aging can alter the shape of stress-strain curves as shown in Figure 17 and 18 [15]. The strain aging leads to the appearance of Lüder's extensions in the stress-strain curves. The Lüder's extension is particularly detrimental to the compressive strain capacity of pipelines.

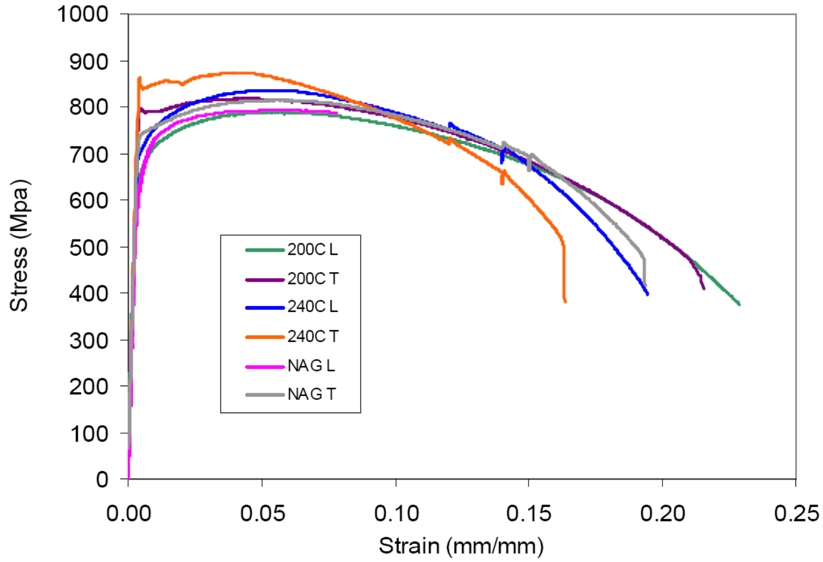


Figure 17. Effect of strain aging temperature on the stress-strain curves of an X100 pipe

3.6.3 Effect of Aging Temperature and Pre-Strain on Pipe Properties

The impact of strain aging is closely related to the aging temperature, duration at the aging temperature, and the pre-strain condition of pipes. The increase in the aging temperature leads to the increase of yield strength, as shown in Figure 18. However, strain aging at temperatures below 200°C has little effect on the mechanical properties of pipes.

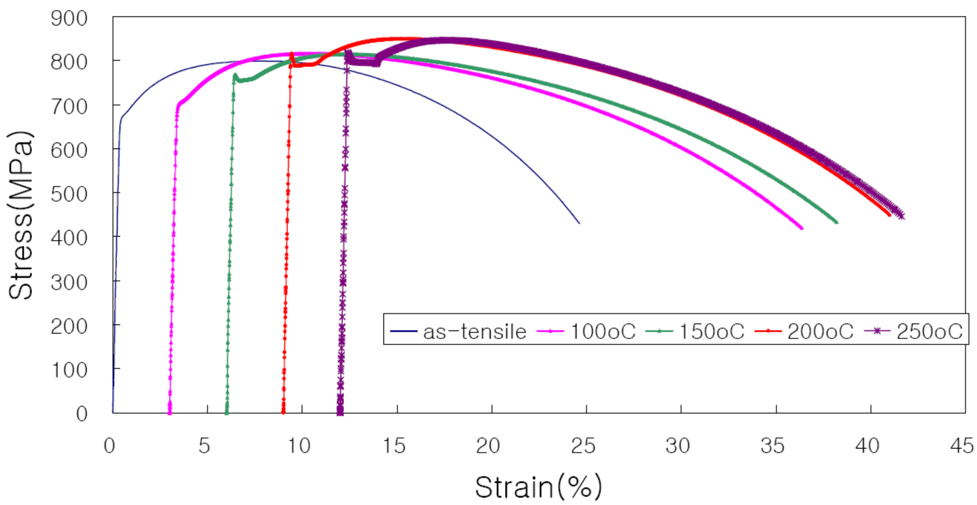


Figure 18. Stress-strain curves of an X100 plate deformed first by 1% strain in the tensile direction and then aged at various temperatures [15]

The amount of pre-straining prior to the aging process influences the extent of mechanical property change. The increase in the pre-strain leads to higher yield and tensile strength of the pipes as shown in Figure 19. The extent of Luder's extension also increases with the increased pre-strain. This sensitivity to pre-strain is at least partially responsible for the different strength and stress–strain curves at different thickness locations of the pipe after aging [15]. Materials at different thickness locations experience varying degree of pre-strain in the pipe forming process. The difference in the amount of pre-strain leads to the different tensile properties.

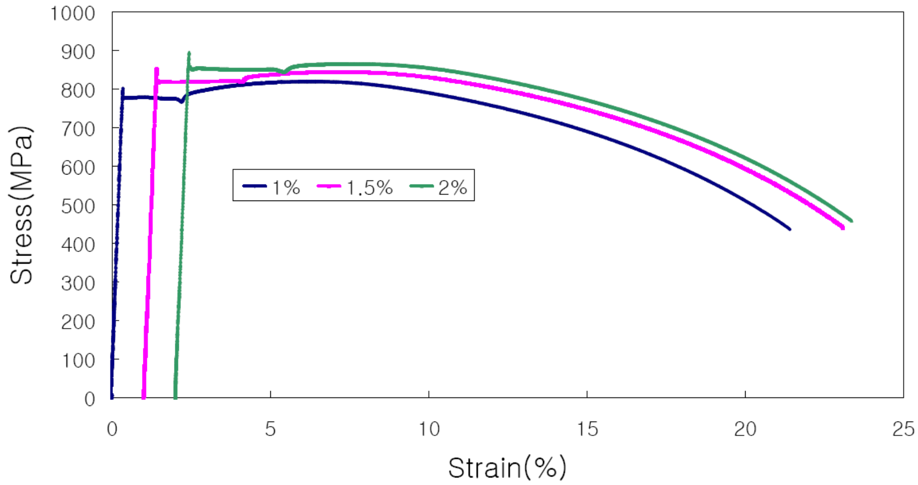


Figure 19. Stress-strain curve of X100 plate aged at 250°C after deformed by various amount of strain through tensile direction [15]

3.6.4 Summary of the Effects of Strain Aging on Linepipe Properties

Numerous studies have been conducted on the effects of strain aging on the tensile properties of high strength pipe. The results of these studies are briefly summarized here.

(a) Strain aging can increase the yield strength by 60 MPa or more [4].
(b) The change in UTS by strain aging is generally much smaller than that in yield strength [4].
(c) Strain aging can change the stress-strain curve from round-house shape to discontinuous yielding [4].
(d) There is a strong correlation between the change in stress-strain curves and the (1) amount of pre-straining, (2) strain aging temperature, and (3) duration of the temperature hold [19].
(e) The tensile property change may vary at different pipe wall thickness locations as those locations experience different amount of pre-strain [15].
(f) Most reported linepipe steels don't experience significant strain aging effects at temperatures below 200°C when subjected to the typical duration of anti-corrosion coating (e.g., FBE coating of approximately 5 minutes).

4 IMPACT OF LINEPIPE PROPERTIES ON PERFORMANCE

4.1 IMPACT OF YIELD STRENGTH DEFINITION

The yield strength is perhaps one of the most fundamental parameters that affects all phases of a pipeline's life, including design, construction, and maintenance. Having proper representation of the yield strength is critical for a wide range of considerations.

- One of the fundamental problems in having a yield strength defined on the elastic part of the stress-strain curve is that the reported values can have huge variations from one test to another, even when the overall stress strain responses are almost identical. This variation creates uncertainties of the pipe strength which affect all stakeholders, including pipe mills, owner companies, and designers.
- Strain hardening has been recognized as one of the critical parameters in strain-based design [20]. The strain hardening capacity of linepipe materials is often expressed in terms of Y/T ratio. The possible under-representation of the yield strength leads to overly optimistic representation of the strain hardening capacity.
- One of the critical considerations in strain-based design is the weld strength mismatch level. It is now generally accepted that weld strength overmatching is preferred for strain-based design. If the yield strength of the pipe material is "misrepresented," the weld mismatch level can't be satisfactorily specified.
- Consumable manufacturers rely on the mismatch requirements for their product development and delivery. When the yield strength of the pipe material is artificially under-represented, pipe mills may choose to increase the overall strength level to meet yield strength requirement. The increased strength level of the pipe would lead to the increased strength requirement of the weld metal. At a very high strength level, the weld metal ductility and toughness may suffer.
- The under-representation of the yield strength can give an impression that the weld metal overmatches the pipe material by a very large margin if the strength mismatch is measured by the yield strength. The examination of the full stress-strain curves would suggest otherwise.

4.2 SIGNIFICANCE OF ANISOTROPY

The anisotropy of linepipe materials has been examined by a number of researchers around the world [10,21,22,23]. The effects of the material anisotropy on the pipeline integrity can be significant. For instance, Brushchi et al. [23] found that a 15% reduction of the compressive yield strength in the transverse direction can reduce the longitudinal compressive strain limit to 50% of the pipe without anisotropy for a pipe at 2150-meter water depth.

1.1.1 Effects of Anisotropy on Tensile Strain Capacity

When the tensile strain capacity of a pipeline is examined, it is generally thought that the strain capacity is dominated by the longitudinal property. Liu and Wang [24] studied the effects of material anisotropy on the crack driving force of a pipe with a surface-breaking flaw of 3-mm deep and 25-mm long in a 3-D finite element model. The pipes were subjected to various levels of internal pressure prior to being loading in the longitudinal direction. Two material models were used. The first one was a traditional isotropic hardening model, in which the stress-strain curve is very similar to the longitudinal curve in Figure 7. The second one was an isotropic/kinematic hardening model, which captured material's anisotropy. The stress-strain curves are different in longitudinal and transverse directions (similar to the curves in Figure 7). The calculated CTOD driving force curves are shown in Figure 20. Under the internal pressure equivalent to a Class 1 design (hoop stress = 72% SMYS), the crack driving force from the isotropic/kinematic hardening model is much higher than that from the isotropic hardening model. The analysis results show that the stress-strain response in the transverse direction affects the plasticity at the crack tip and in the remaining ligament of a **c**ircumference flaw, thus affecting the cracking driving force. In other words, the properties in transverse direction of pipe can significantly affect the strain capacity of pipe, especially when the pipe is subjected to internal pressure.

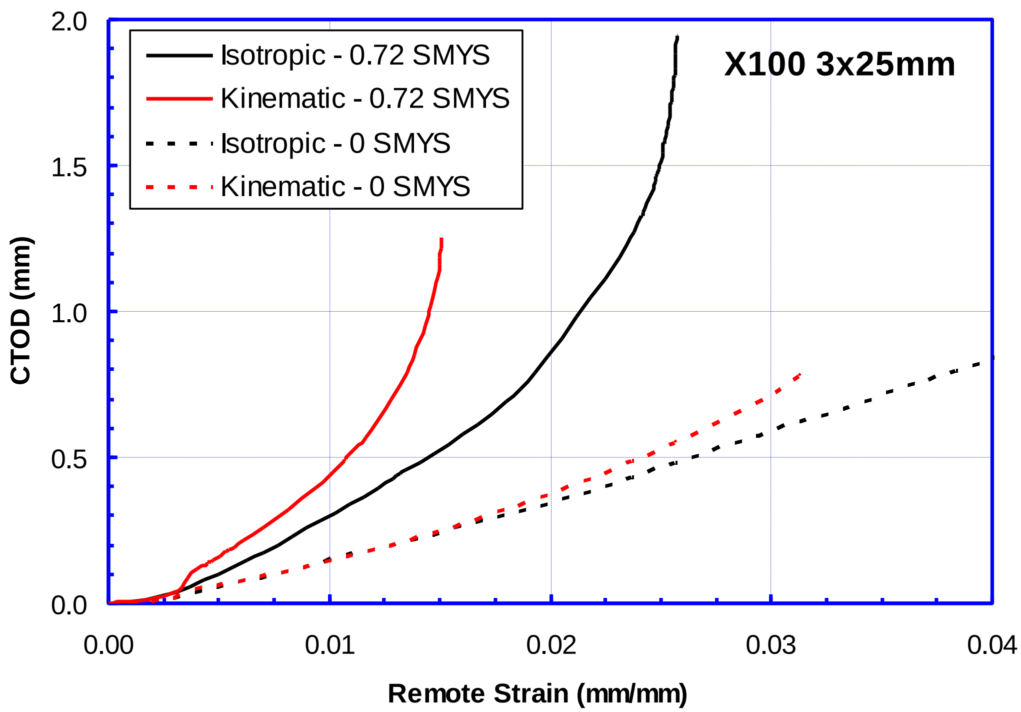


Figure 20. Crack driving force as a function of remote strain in the longitudinal direction for two material models at two levels of internal pressure

4.2.1 Effects of Anisotropy on Buckling Resistance

The anisotropy in material's tensile properties can also affect the integrity of the linepipes such as their buckling and collapse resistance. For instance, the critical strain at buckling can differ by a factor of almost two if either the transverse or the longitudinal stress strain relation is used in a model assuming isotropic material properties, as shown in Figure 21 [10]. To achieve conservatism, the material properties in the direction of the minimum strain hardening and the highest Y/T ratio are often used in the isotropic models [25]. However, this simplification may lead to an under-estimation of the buckling resistance.

Liu and Wang [10] studied the dependence of buckling resistance of an X100 pipe with 36-inch diameter and 0.5-inch (12.7-mm) wall thickness on the plasticity models. These plasticity models have different degree of capability in incorporating material's anisotropy. The plasticity models were tuned by the experimental tensile and/or compressive stress-strain curves. These models were then used to simulate the buckling behavior of the full-size pipe.

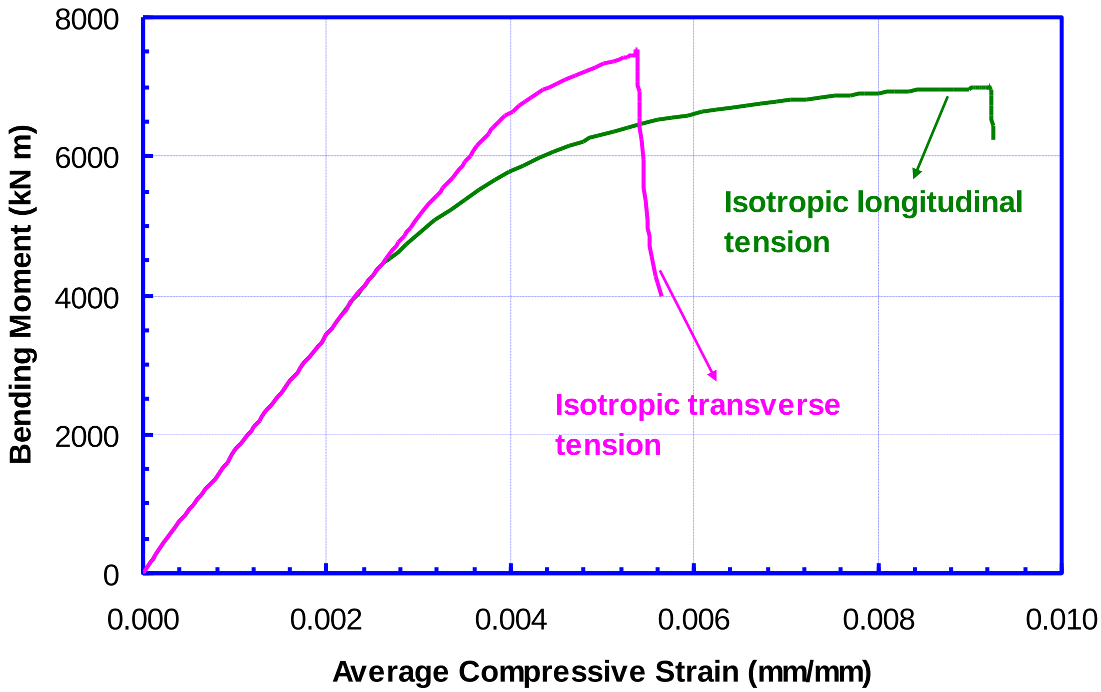


Figure 21. Predicted relations of bending moment vs. average compressive strain assuming isotropic material properties

Figure 22 shows the predicted bending moment vs. compressive strain relations from various plasticity models. The isotropic model with the tensile transverse property gives the lowest buckling strain. In contrast, the isotropic model with the tensile longitudinal property gives the highest buckling strain. Situated between those two models is the kinematic hardening model with two different pre-strain histories, which can account for the anisotropic behavior of material. The pre-strain histories reflect the pipe forming process which is one of the primary causes of the anisotropic tensile properties. In one case, a 2% uniaxial tensile strain was pre-applied in the transverse direction to simulate the expansion procedure of the UOE process. In the other case, the 2% strain was applied in the transverse direction while keeping the ends of pipe fixed in the longitudinal direction, i.e., in a plane strain condition. The stress-strain response from the second case was much closer to the measured longitudinal compressive stress-strain curve than that from the first case. The differences in tensile stress strain response and the transverse compressive curve between the two pre-strain modes were small. Therefore the pre-strain applied in the plane strain condition produced more representative stress strain response.

The predicted pipe response under lateral bending shown in Figure 22 may be compared with the critical buckling strain from codes and published equations. Liu and Wang selected the buckling strains from the classical elastic equation for the local buckling [26], Stephens [27], CSA Z662

2003, and DNV-OS-F101 for comparison. Figure 23 shows the predicted bending moment vs. compressive strain relations from the different plasticity models and the critical strains from the selected codes and published equations. The classic elastic solution is overly optimistic and not suitable for estimating the critical buckling strains. CSA Z662 2003 comes closely to the best predicted critical strain (from the kinematic model with pre-strain applied under the plane strain condition), but still produces only one half of the predicted strain capacity. Overall, none of the selected equations is accurate in correlating the critical buckling strains. The analysis of Liu and Wang demonstrates the importance of having appropriate plasticity models and the potential role of anisotropy in accurately predicting the buckling behavior of linepipes. The codified equations of buckling strains are typically from semi-empirical correlation of experimental test data. Most of these tests are done with pipes of older materials. The applicability of those equations to high strength TMCP linepipes which can have strong anisotropy should be further investigated.

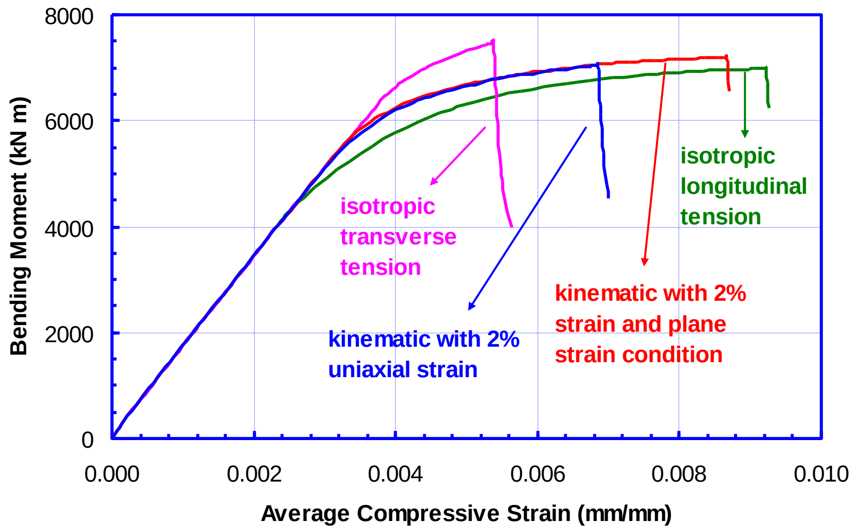


Figure 22. Comparison of bending moment vs. compressive strain relations from different plasticity models

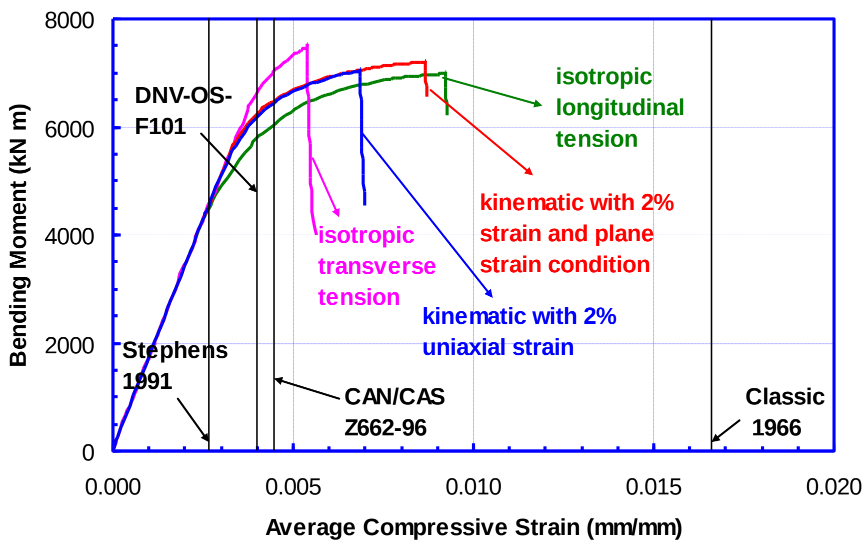


Figure 23. Bending moment vs. compressive strain relations from different plasticity models and comparison with critical strains from codes and published equations

Tsuru et al. [22] studied the dependence of buckling resistance of different pipes subjected to bending moment and high internal pressure. In addition to the traditional Hill's quadratic anisotropic yield function, a modified Hill's anisotropic yielding material model was incorporated into finite element simulation. The results indicated that the difference in the longitudinal compressive strain limits from isotropic and anisotropic yield functions increased with the increase of internal pressure and pipe wall thickness.

4.3 IMPACT OF UPPER LIMITS ON STRENGTH

One of the major concerns about the upper limits of yield strength and UTS is that it affects weld metal strength mismatch level. The weld strength overmatch relative to the pipe body strength is generally considered preferable in design and construction to prevent strain localization in the weld region. The weld mismatch level is commonly indexed to the yield strength of the weld metal and the base metal (pipe body). Wang, et al., proposed that the weld strength mismatch should be preferably indexed to the UTS as the UTS of pipe and weld metal is a more stable indicator of the strength of the materials [28]. The yield strength, as it is measured by the current customary methods, is sensitive to minor changes in the shape of the stress-strain curve.

The wide range of tensile properties permitted for a given grade of linepipes, shown in Table 2 as an example, makes it difficult to select proper consumables and welding processes to achieve certain level of desired mismatch. For instance the specified minimum yield strength of X80 pipes are 555 MPa and the upper bound of the yield strength is 705 MPa. If the yield strength of the weld is at 630 MPa, the average of the SMYS and the upper bound yield strength, this can result in 13.5% overmatching if the pipe yield strength is at the SMYS or 10.6% undermatching if the pipe yield strength is at the upper bound value of 705 MPa. To achieve consistent overmatching, the lower bound of the weld strength would have to be higher than the upper bound pipe strength. For X80 pipes this would imply that the yield strength of the weld has to be greater than 705 MPa and the UTS greater than 825 MPa (120 ksi). Having the weld metal at this strength level while maintaining adequate toughness and ductility can be difficult. For pipes grades greater than X80, achieving consistent weld strength overmatching become even more challenging.

4.4 Y/T RATIO AND STRAIN HARDENING

4.4.1 <u>Strain Hardening of High Strength Linepipes</u>

In strain based design, material's strain hardening capacity is a crucial factor that affects the strain capacity and integrity of the pipeline. Modern high-strength linepipe materials made from low carbon micro-alloyed TMCP steels typically have lower strain hardening capacity (high Y/T ratio) than older linepipes made from hot-rolled and/or quench-and-tempered steels. The strain hardening capacity typically decreases with the increase of pipe strength.

The Y/T ratio is often used as a proxy to material's strain hardening capacity. This simplified representation is only meaningful when the reported yield strength of the material is reasonably close to the physical yield strength. As shown in Section 3.3, the reported yield strength may under-represent the physical yield strength when there is nonlinearity in material's elastic part of the stress-strain curve.

4.4.2 Effects of the Stress-Strain Curve on Compressive Strain Capacity

Yatabe, *et al.*, studied the effect of material stress-strain curve shape on the strain capacity of X80 pipes by finite element analysis [29]. Two stress-strain curves of different shape were created. These curves have the same Y/T ratio of 0.90 and a uniform strain of 12% as shown in Figure 24 (Curve 1 and Curve 3). The pipes were subjected to either uniform compressive deformation or lateral bending deformation. The results of the uniform compressive deformation are shown in Figure 25. It can be seen that Curve 1 gives higher compressive deformation capacity than Curve 3. The results of the bending deformation are shown in Figure 26. The Curve 1 provides higher bending deformation capacity than Curve 3. These results demonstrate that the shape of the stress-strain curve affects the strain capacity even when the Y/T ratio is the same. Therefore full stress-strain curves are needed in characterization of material's strain capacity.

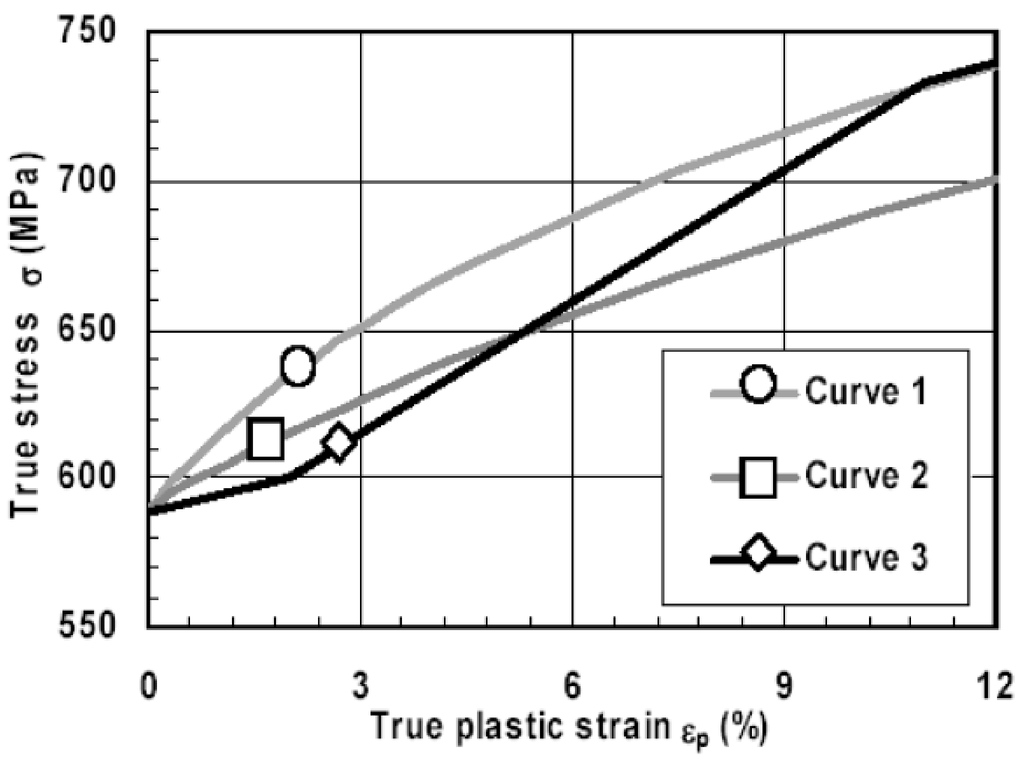


Figure 24. Material stress-strain curves used for FE analysis [29]

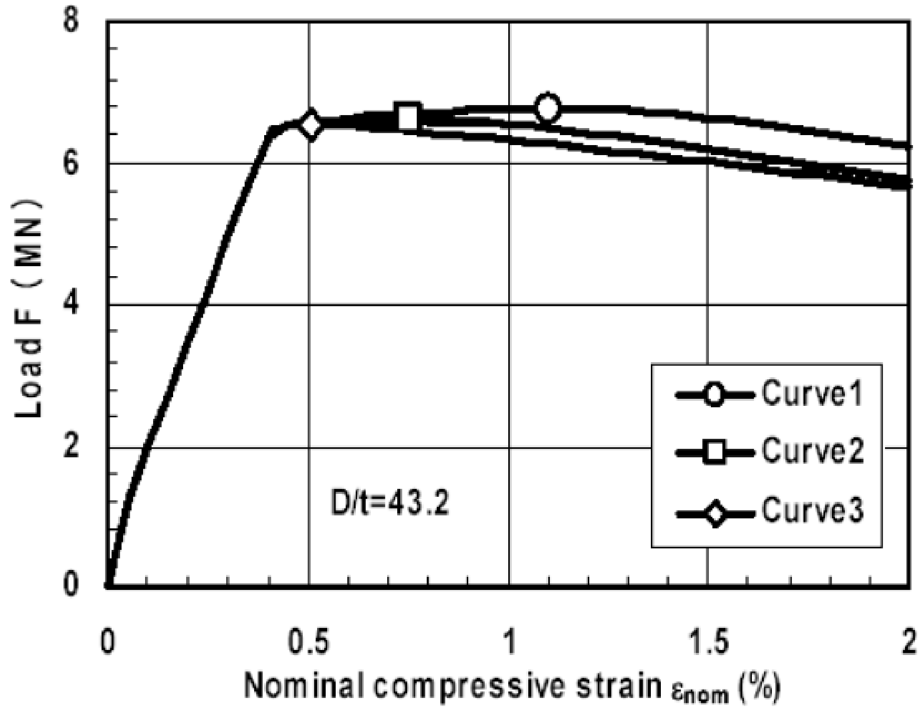


Figure 25. Effect of stress-strain curve shape on the pipe compressive deformability [29]

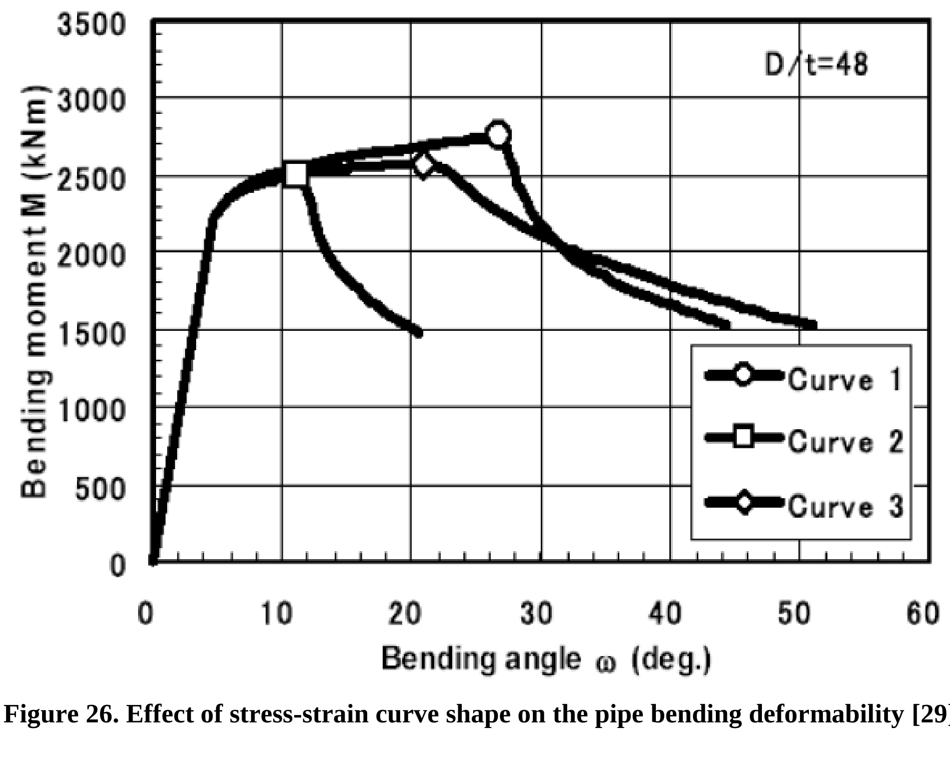


Figure 26. Effect of stress-strain curve shape on the pipe bending deformability [29]

5 FORMAT OF LINEPIPE SPECIFICATIONS

5.1 LINEPIPE SPECIFICATION FOR STRAIN-BASED DESIGN IN PIPELINE PROJECTS

TransCanada PipeLines Ltd. installed one kilometer of trial section of X100 pipeline in the fall of 2002 [30] and then two kilometers of X100 pipeline in the winter season of 2003-2004 [31]. A 5.5 kilometer section of X100 pipeline was installed in 2006 with fully strain-based design requirements [32]. Additional requirements of the linepipe were implemented to supplement those in CSA Z245.1-02 [33]. Some of these supplemental requirements are (1) round bar tensile tests for hoop properties, (2) tensile tests in the form of strip specimens for longitudinal properties, (3) different minimum and maximum yield strengths for the hoop and longitudinal directions, (4) different maximum Y/T ratios for hoop and longitudinal directions, and (5) minimum uniform elongation in the longitudinal direction. Multiple stress ratios at predefined strain intervals were also required for the longitudinal tensile properties to ensure that “round–house” stress-strain relations were achieved [32].

5.2 SCOPE OF THE RECOMMENDED SPECIFICATIONS

The scope of the recommended specifications includes,

(1) tensile specimen forms and dimensions,
(2) definition of yield strength,
(3) consideration for strain aging,
(4) hoop vs. longitudinal properties (anisotropy),
(5) upper limits on yield strength and UTS, and
(6) representation of strain hardening capacity.

5.3 GENERAL CONSIDERATIONS FOR MATERIAL PROPERTY CHARACTERIZATION

In addition to the material features covered in Sections 3 and 4, there are a few broad issues related to the material testing. These issues are highlighted here and subsequently incorporated into the recommended format for linepipe specifications.

5.3.1 Material Test Temperature

The test temperature affects the measured tensile and toughness properties. For instance, test data shown in Sections 3 and 4 have demonstrated that that the strain hardening capacity and uniform elongation of linepipe and weld metal can increase at -20ºC in comparison to the corresponding properties at room temperature. There is some evidence that the fracture resistance curves may also increase at a cold temperature than that at the room temperature, possibly related to the rise of material’s strain hardening at the cold temperature. This trend would only exist when the test temperature is not sufficiently cold to trigger cleavage fracture, i.e., low shelf behavior. In general the material test temperature should be selected to correlate with the postulated failure events.

5.3.2 Tensile Test Data and Test Form

Tensile test data are affected by specimen dimensions, instrumentation setup, and even post-test data processing. For instance the total elongation from round bar specimens is lower than that from rectangular cross-section specimens of the same material. A material specification should include both required property values and the test protocols to be used to generate the data.

5.3.3 Property Variations of Nominally the Same Material

Both tensile and toughness properties can have variations at the same grade or strength level. The tensile property variations of linepipe and weld can lead to a range of weld strength mismatch levels. Toughness properties are affected by notch location and notch depth. These variations should be considered in the design and material selections.

5.4 LINEPIPE SPECIFICATIONS RELEVANT TO STRAIN-BASED DESIGN

5.4.1 Tensile Test Temperature

Small-scale and limited large-scale tests conducted have shown that the linepipe steels can have higher strain hardening capacity and increased uniform elongation at -20ºC than at room temperature. Consequently it is necessary to consider the effects of temperature in specifying material qualification tests.

Ideally tensile tests should be done at temperatures corresponding to the postulated failure events. Alternatively the effects of temperature should be considered by applying empirical corrections that are relevant to the materials of interest.

5.4.2 Specimen Dimensions of Tensile Tests

Tensile properties, particularly strain hardening capacity, are a significant influencing factor in tensile strain design. The tensile test data are affected by specimen dimensions, instrumentation setup, and even post-test data processing.

5.4.2.1 Test for Hoop Properties

- Round-bar specimens without flattening should be tested for hoop properties.
- Within the reduced gauge section of the specimen where the test data are taken, the length over the diameter ratio should be equal or greater than 4.
- The mounting points of the clip gages should be sufficient far away from the shoulders of the specimen (the transition zone from the reduced gage section to the end tab) to assure uniform deformation within the gage section.
- The diameter of the reduced gage section should be as large as possible while meeting the requirement of length to diameter ratio.

5.4.2.2 Test for Longitudinal Properties

- Full thickness strap or round-bar specimens should be tested for longitudinal properties.
- The specimen should be of "dogbone" shape with a reduced gage section in the middle of the specimen.
- No parallel-sided strip specimens, similar to those in the main body of API 1104 20th Edition, should be used.
- Within the reduced gauge section where the test data are taken, the length over the diameter/thickness ratio should be equal or greater than 4.
- The mounting points of the clip gages should be sufficient far away from the shoulders of the specimen to assure uniform deformation within the gage section.
- The diameter of the reduced gage section should be as large as possible for the round-bar specimens.
- Different total elongation may be specified for the round-bar or full-thickness specimen.

5.4.3 Definition of Yield Strength

The accurate characterization of material's strain hardening capacity, as often represented by the Y/T ratio, is critical for strain based design. When the reported yield strength is lower than the physical yield strength, the resulting low Y/T gives an overly optimistic representation of the material's strain hardening capacity. This Y/T ratio can lead to overestimation of the tensile strain capacity.

The accurate representation of material's yield strength is a prerequisite for specifying proper weld strength to achieve certain desired level of weld strength mismatch. Artificially low yield strength can give a misleading impression of weld strength overmatch.

The proper definition of yield strength has profound impact on all aspects of pipeline's life. The long-term solution to the issue highlighted in Sections 3 and 4 is the revision of relevant linepipe standards. The fundamental issue is that the strain at which the yield strength is defined needs to be correlated to the overall strength of the material. The current definition is good for lower strength material, but not sufficient for high strength materials, particularly materials with nonlinear elastic behavior prior to yielding.

In the case of materials exhibiting non-linearity prior to the physical yield point (defined here as the knee of the elastic to plastic transition on a stress-strain curve) as shown in Figure 10, yield strength defined by an offset strain, as opposed to a total strain, does not alleviate the possibility of reporting artificially low yield strength.

Two possible options may be considered to revise the definition of the yield strength to the physical yield strength of the materials can be accurately captured.

The first option is to set the strain value at which the yield strength is defined as a variable that is tied to the pipe grade. For instance, the strain value may be set at 0.5% for X70 and 1.0% for X100. A linear scaling factor may be applied to grades in between. For instance, the strain at which the yield is defined for X80 would be $0.5+1/3\times0.5=0.67\%$ and 0.83% for X90. The downside of this approach is that the actual strength of a pipe of the same grade can vary greatly. If the actual yield strength of an X80 pipe is close to 100 ksi, the yield strength would still be defined at 0.67% strain.

The second option is defining the yield strength by specifying a predefined slope on the stress-strain curve. The "turning point" from elastic to plastic part of the curve is the yield point. The definition is theoretically the most rigorous. However it can be difficult to apply within the framework of the current practice. Most of the test machines are not set to produce full stress-strain curves. The technology is available, however, to automate the data acquisition and post-test data processing so the yield strength can be uniquely determined from the stress-strain curves.

The need for revising or amending the yield strength definition, however, can't be overemphasized. In the absence of code revisions, the prudent practice for owner companies and designers is to request yield strength at several strain levels and full stress-strain curves. One should always be cautious when a single yield strength value is reported by the current definition, particular for grades X80 and above.

5.4.4 Strain Hardening

The accurate characterization of material's strain hardening capacity, as often represented by the Y/T ratio, is critical for the characterization of pipeline's strain capacity. When the reported yield strength is lower than the physical yield strength, the resulting low Y/T gives an overly optimistic representation of the material's strain hardening capacity. This Y/T ratio can lead to overestimation of pipeline's strain capacity.

If a Y/T ratio were to be used as a proxy for material's strain hardening capacity, the definition of yield strength needs to be updated to reflect material's physical yield strength. Alternatively, the strain hardening capacity may be represented by the strain hardening exponent in a typical power-law fitting of the stress-strain curves, e.g., in the form of CSA Z662 format or Ramberg-Osgood format.

It should be recognized that the stress-strain curves of the modern "high-strain" pipes, similarly to that of Figure 10 typically do not fit into one single CSA Z662 or Ramberg-Osgood stress-strain relation. In the low strain range (e.g., when the engineering strain ≤ 3%), the plastic part of the stress-strain curve typically have much high strain hardening than that of the high strain range. Consequently these two parts of the curves cannot be fitted into a CSA Z662 or Ramberg-Osgood stress-strain relations with a single strain hardening exponent.

5.4.5 Data Check of Tensile Test Results

5.4.5.1 Data Check for Elastic Slope

The reported yield strength from the stress-strain curves similar to that of Figure 10 is especially sensitive to the initial slope of the stress-strain curves. Similarly stress ratio requirements, such as those suggested by TransCanada [30,31,32], are highly sensitive to the initial slope. Even in the absence of nonlinear elastic behavior, the reported yield strength of high strength material is sensitive to the initial slope of the stress-strain curve.

To reduce the possible error in the reported yield strength the (thus *Y*/*T* ratio), the initial part of the stress-strain curve should checked against theoretical elastic modulus. The initial slope of the stress-strain curve at the stress level up to 1/3 of the ultimate tensile strength should be computed and compared with the elastic modulus. If the initial slope is more than 10% off the theoretical value, the possible sources of the discrepancy should be examined. These sources may include, but not limited to, specimen straightness, placement of clip gage, test machine alignment, etc. After the possible sources of systematic errors are eliminated, the test data may be updated by applying a compliance correction.

5.4.5.2 Data Check for Uniform Elongation

The determination of uniform elongation (strain) may not be as simple as it seems when the stress-strain curves are very flat around the point of UTS. Digital data records often have small local oscillations. An occasional spike may produce the maximum value of stress. Such an individual spike may not represent the maximum stress point when the data are viewed by a generation trend line. The general trend line is a better representation of the material behavior.

When the stress strain curves are flat around the point of UTS, a curve fit around the point should be conducted to “smooth” out the local data oscillations. The point of UTS should be determined by obtaining the maximum stress level of the fitted curve. The corresponding uniform elongation is obtained accordingly from the same procedure.

5.4.6 Definition of “Round-House” Behavior

5.4.6.1 Various Forms of “Round-House Behavior

Some of the recent efforts to produce pipes with superior strain capacity have focused on having “round-house” stress strain curves. The presence of yield point elongation, or Lüder’s extension, tends to initiate buckling, and therefore reduces compressive strain capacity of the pipe. Therefore having round-house stress strain curves is critical to achieve high compressive strain capacity.

Conceptually the round house stress strain curve is such that the yielding is continuous. i.e., the stress increases smoothly and gradually with the increase of strain, sees Figure 27. Published data have shown that such stress-strain curves are achievable before the pipes are subjected to anti-corrosion coating. However, a yield plateau can appear after anti-corrosion coating, see Figure 28. Sometimes a slight drop in load can occur around the yield point, Figure 29. A very small yield plateau or even a small load drop may not affect the overall material behavior in a full-scale pipe. However there is likelihood that materials with such stress-strain curves could be disqualified by the current rather ambiguous definition of round house behavior.

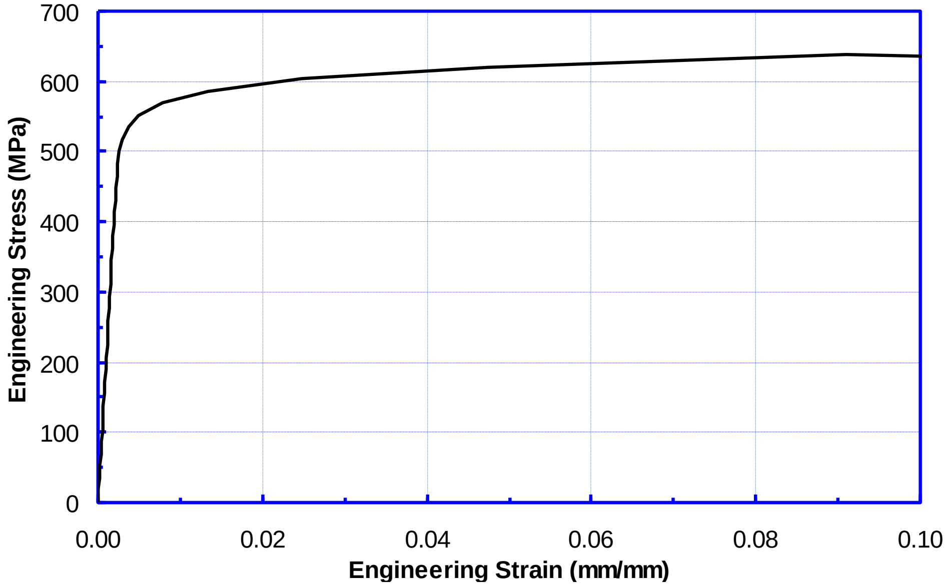


Figure 27. A stress-strain curve that would be qualified as having "round-house" shape

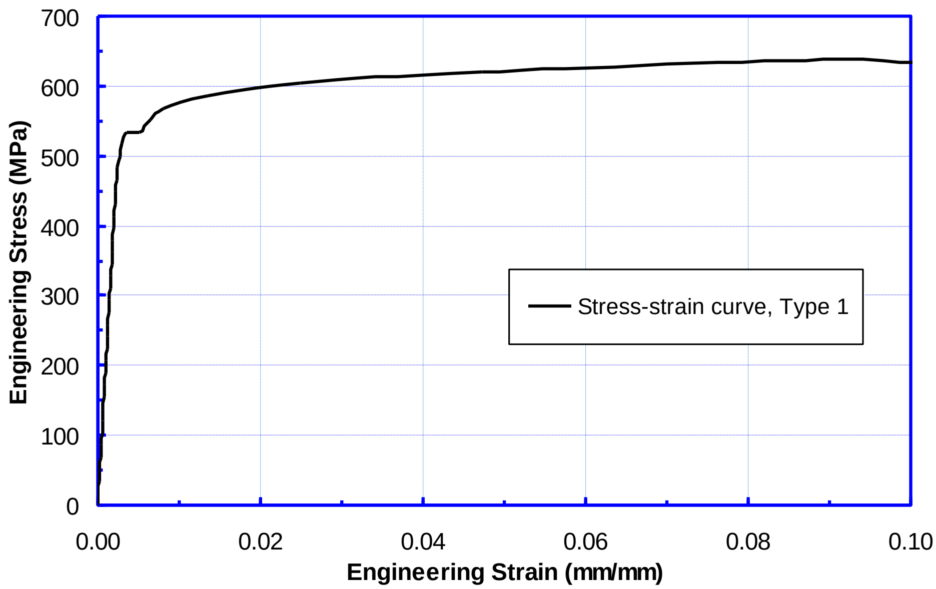


Figure 28. A possible stress-strain curve with a small plateau after anti-corrosion coating

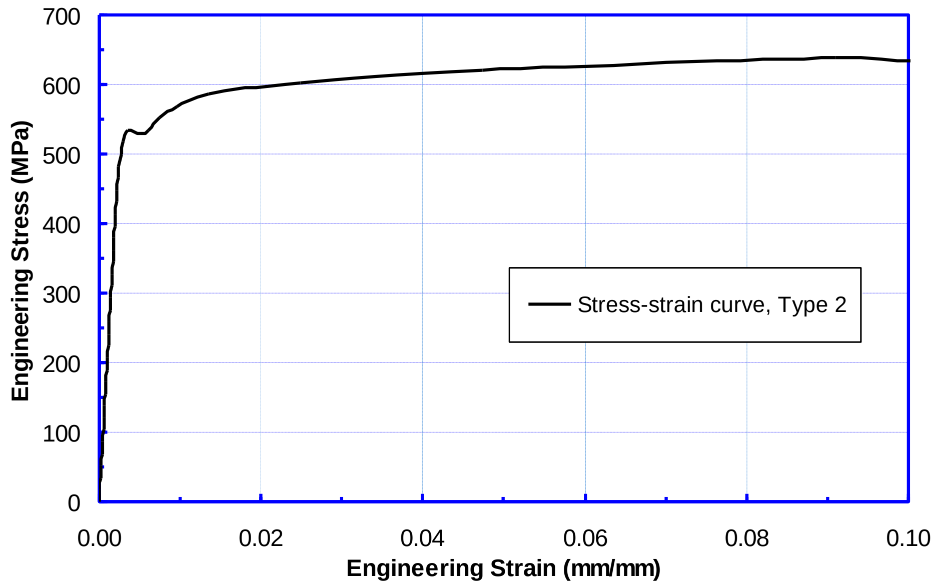


Figure 29. A possible stress-strain curve with a small load drop at yield after anti-corrosion coating

5.4.6.2 Specifying Round House Behavior by Stress Ratios

TransCanada used multiple stress ratios as a mean to achieve round-house stress-strain curve [32] as shown in Figure 30. A few practical challenges may exist for such approach when it is used over multiple orders of linepipes from multiple supplies, as in the case of a large-scale pipeline project.

- The significance to strain capacity is not clear if one of the stress ratios cannot be met.
- Small dips in the strength on the stress-strain curves are theoretically possible even the stress ratios are met.
- The quality of the tensile data needs to be very high and consistent so the materials would not be mistakenly disqualified.

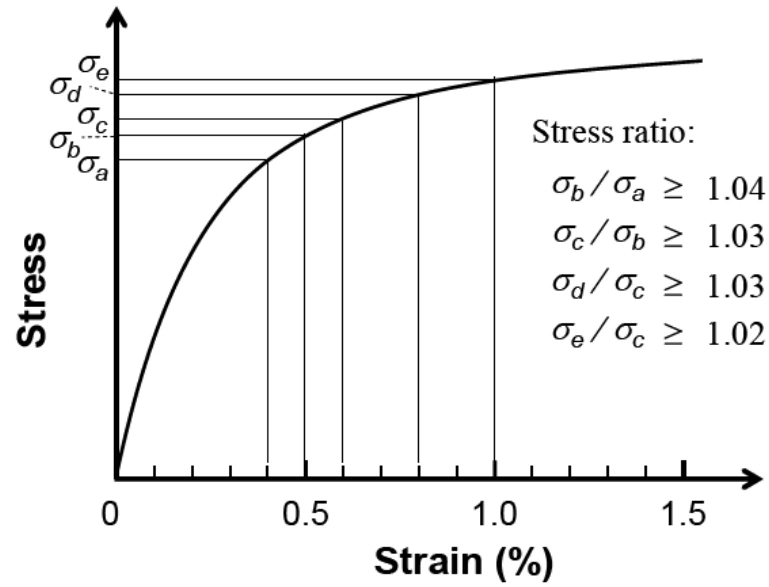


Figure 30. Definition of the stress- ratio in CSA Z245.1-02 supplement σ_a: stress at ε=0.4%, σ_b: stress at ε=0.5%, σ_c: stress at ε=0.6%, σ_d: stress at ε=0.8%, σ_e: stress at ε=1.0%

5.4.6.3 Recommended Options to Define Round House Behavior

A more robust definition of round-house behavior is needed. The definition should focus on two factors: (1) the magnitude of the stress drop and (2) the strain interval over which the drop occurs. It may be argued that an isolated small drop or plateau in stress over a very small strain range should not adversely affect tensile strain capacity, particularly if the overall strain hardening trend is continuous.

The following definition is proposed for the portion of the stress-strain curve with the strain less than 50% of the uniform strain, "a stress-strain curve is deemed to have round-house shape if any region in which the stress decreases is limited to a stress drop no greater than 0.5% of UTS and a strain range no greater than 0.2%."

Such a definition would allow for a plateau or even drop in stress value, provided that this occurs within a small strain increment of 0.2%. This proposed definition is meant as a starting point for defining a critical requirement in the environment that the term "round-house shape" does not have a precise definition. Such a definition is meaningful from the viewpoint of required performance and at the same time would not lead to needless rejection of pipes which can perform satisfactorily. The implementation of such a definition is possible with digital records of stress-strain curves and relatively simple post-test data processing software.

5.4.7 Summary Considerations

5.4.7.1 Recommendations and Rationales

The sensitivity of strain-based design to linepipe and weld tensile properties is well established. The current specifications in codes and standards are far from sufficient to guarantee tensile properties adequate for strain-based design. The following considerations are recommended.

1. At a minimum, full stress-strain curves are required for pipe and weld tensile properties.
2. The quality of the full stress-strain curves may vary and should be checked and confirmed. One particularly obvious “marker” is the reported elastic slope of the stress strain curves. While the elastic slope is generally not viewed as a material parameter in strain-based design, the elastic slope directly affects the reported yield strength. This influence is particularly acute for stress-strain curves of high-strength steel exhibiting non-linear behavior prior to the yield point, see Figure 10. An incorrect elastic slope can directly lead to incorrect yield strength, hence incorrect Y/T ratio and incorrect conclusion on the pass/fail of the strength requirement. It also affects the qualification of the weld strength mismatch if the mismatch is defined at the yield strength. It is recommended that consistent test data-screening and evaluation procedures be implemented in project applications.
3. The effect of test temperature on the strain hardening behavior is a relatively new issue. More investigation is needed given the importance of strain hardening capacity on tensile strain limit. With respect to the overall approach to strain-based design, consistency in test temperature should be considered. Although the pipeline industry has been conducting toughness tests (e.g., Charpy and CTOD) at the minimum design temperature or lower, tensile tests are mostly done at room temperature. Yet tests specific for strain-based design, such as curved-wide-plate tests, may be done at yet another temperature. There is a need to (1) understand the temperature effects on tensile properties, (2) move towards a uniform test temperature so the test results can be better correlated.
4. The yield strength according to current definitions, either at 0.5% total strain or at 0.2% offset strain, can exhibit large specimen-to-specimen variations. This is particularly true for longitudinal property measurement in some of the high strength pipes. It is recommended that the strain at which the yield strength is measured be graduated (increased) with pipe strength level.
5. The shape of stress-strain curves is affected by the material properties and the way the tests are done. Consistent tensile test protocols, including both linepipe and girth welds, are needed.
6. It is insufficient to define weld strength mismatch on the basis of either yield strength or UTS. Given the relatively large spread in the yield strengths of both pipe and weld metals, defining strength mismatch on the basis of yield strength can be problematic. The UTS of both pipes and welds tends to show less variation than the yield strength for the same welds. The strength mismatch on the basis of UTS is preferred to that based on yield strength. If a single value indicator is desired, mismatch based on UTS should be used.

7. Strain hardening capacity is a critical parameter for strain-based design. The customary representation of strain hardening by Y/T ratio is not adequate if the reported yield strength does not represent material's true physical yield point.
8. The round house definition on the basis of the amount of stress drop and the strain range over which this drop may occur should be adopted.
9. The proper characterization of "high-strain" pipes should be examined. The significance of customary parameters, such as Y/T ratio, should be evaluated against the linepipe materials that have been in service for decades.
10. The allowance of extremely high Y/T ratio for high strength linepipes, e.g., Y/T limit of 0.99 for X120, brings a new set of unknowns. Certain stress-based design and maintenance criteria, such as corrosion assessment tools and ductile fracture initiation criteria, have certain implicit assumptions about material's strain hardening capacity. The applicability of those criteria in the context of very high Y/T ratios is unknown and should be critically evaluated. Furthermore, pipelines designed by traditional stress-based principles may still experience certain displacement-controlled loading after the pipelines are put in service. Any potential use of very high Y/T materials changes the implicit safety factors that the industry has had a successful experience.
11. Some features of longitudinal tensile properties, such as Y/T ratio, are often viewed as more important in strain-based design than those of hoop properties. In should be recognized that the principles of stress-based design are still in effects for pressure containment even when the pipelines are subjected to high longitudinal strains. For in-service pipelines, the sequence of pressure loading and longitudinal straining can change over time and there could be multiple loading cycles. Both hoop and longitudinal properties can have influence on the overall integrity of the pipelines. Furthermore the effects of anisotropy in tensile properties should be examined.

The summary tensile property requirements are given in Table 6. The rationales for those requirements have been covered in previous sections. The generic issues are relevant to both stress- and strain-based designs. In addition to the generic issues, reducing the upper bound of strength distribution can yield benefits for both design conditions. For strain-based design, the additional requirements are associated with the longitudinal properties and the characterization of full stress-strain curves.

Table 6. Recommended test requirements for strain-based design

Property Parameters	Orientation	Features	Current Requirement	Stress-based design in addition to the generic issues	Strain-based design in addition to the generic issues	Generic Issues to Be Considered
Yield Strength and UTS	Hoop	Test Form	Flattened strap	Round bar and/or ring expansion	Round bar and/or ring expansion	Definition of yield strength, test specimen form and dimensions, test temperature, effects of strain ageing, effects of cyclic plastic strain
		Minimum	Yes	Yes	Yes	
		Maximum	No for PSL 1, Yes for PSL 2	Yes	Yes, lower than the current code limits	
	Longitudinal	Test Form	Not required	Optional, Full-thickness strap or round bar	Full-thickness strap or round bar	
		Minimum	Not required	Optional	Yes	
		Maximum	Not required	Optional	Yes	
Y/T Ratio	Hoop	Maximum	No for PSL 1, Yes for PSL 2	Yes	Yes	
	Longitudinal	Test Form	Not required	Optional	Yes	
Total Elongation	Hoop	Minimum	Yes	Yes	Yes	
	Longitudinal	Minimum	Not required	Optional	Yes	
Uniform Strain or Elongation	Hoop	Minimum	Not required	Optional	Optional	
	Longitudinal	Minimum	Not required	Optional	Yes	
Shape of Stress-Strain Curve	Hoop		Not required	Optional	Optional	
	Longitudinal		Not required	Optional	Yes	

5.4.7.2 Other Issues worthy Considerations

A number of other issues important to pipeline integrity and linepipe specifications are worthy of considerations, but not covered extensively here.

1. Toughness specifications related to fracture initiation, prevention of brittle running fracture, and arrest of ductile running fracture are an integral part of linepipe specifications. These specifications are not covered here.
2. The dimensional tolerance of linepipes affects the high-low misalignment at the girth welds and even the compressive strain capacity. The tensile strain capacity of girth welds is particularly sensitive to high-low misalignment. The implication of the linepipe dimension tolerance should be considered for design and fabrication.
3. The alloy design of steels, plate and coil rolling practice, and pipe manufacturing process have profound effects on the resulting mechanical properties of the linepipes. The specifications of these manufacturing parameters leading to the final mechanical

properties are out of the scope of this report. However, they should form an integral part of linepipe specifications as a part of overall quality control.

6 REFERENCES

1 "Specification for Line Pipe," API Specification 5L, 44th Edition, October 1, 2007.

2 "Petroleum and Natural Gas Industries – Steel Pipe for Pipeline Transportation System," ISO 3183, 2007.

3 Bai, D., Collins, L., Hamad F., Chen, X., Klein, R. and Zhou, J., "X100 (grade 690) helical-welded linepipe," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

4 Klein, R., Collins, L., Hamad, F., Chen, X. and Bai, D., "Determination of mechanical properties of high strength linepipe," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

5 Knauf, G. and Spiekout, J., "Effect of specimen type on tensile behavior", 3R International Special Edition 13, 2002.

6 Johnson, J., Hudson, M., Takahashi, N., Nagase, M., Yamamoto, A., "Specification and manufacturing of pipes for the x100 operational trial," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

7 Jenkins, A. and Glover, A., "Advances in High Strength Technology for Natural Gas Transmission", Proceedings of the Fifteenth International Offshore and Polar Engineering Conference", Seoul, Korea, June 19-24, 2005.

8 Chen, X., Collins, L., Hamad, F. and Bai, D., "The evolution and determination of mechanical properties during the manufacturing process of high strength spirally welded pipe", Proceedings of 6th International Pipeline Conference, September 25-29, 2006, Calgary, Alberta, Canada.

9 Liessem, A., Knauf, G., "Investigation of the stress-strain behavior of large-diameter x100 linepipe in view of strain-based design requirements," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

10 Liu, M. and Wang, Y.-Y., "Modeling of Anisotropy of TMCP and UOE Linepipes," Proceedings of the sixteenth International Offshore and Polar Engineering Conference, (ISOPE 2006), Paper No. 2006-JSC-426, San Francisco, USA, May 28 – June 2, 2006.

11 Treinen, J. M., et al., "Anisotropic Behavior of X100 Pipeline Steel," Proceedings of the 18th International Offshore and Polar Engineering Conference (ISOPE 2008), Vancouver, Canada, July 6-11, 2008.

12 Wang, Y.-Y., Liu, M. and Horsley, D.J., "Some Aspect of Material and Welding Specifications for Strain-Based Design of Pipelines", Proceedings of EPRG-PRCI-APIA 15th Joint Technical Meeting on Pipeline Research, Orlando, USA, May 17-19, 2005.

13 Ishikawa, N., Okatsu, M., Shimamura, J., Endo, S., Shikanai, N., Muraoka, R., Kondo, J., and Suzuki, N. "Material Development and Strain Capacity of Grade X100 High Strain Linepipe Produced by Heat Treatment Online Process," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

14 Hara, T., Terada, Y., Shinohara, Y., Hitoshi, A. and Doi, N., "Metallurgical Design and Development of High Deformable X100 Line Pipe Steels Suitable for Strain Based Design," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

15 Seo, D., Yoo, J., Song, W. and Kang, K., "Development of X100 Linepipe Steel with High Deformation Capacity," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

16 Tsuru, E., Shinohara, Y., and Asahi, H., "Evaluation of Precept of Strain Capacity of High Strength UOE Line Pipes Used in Strain-Based Design Applications," Proceedings of the 17th International Offshore and Polar Engineering Conference (ISOPE 2007), Lisbon, Portugal, July 1-6, 2007.

17 Ishikawa, N., Okatsu, M., Shimamura, J., Endo, S., Shikanai, N., Muraoka, R., Kondo, J., and Suzuki, N. "Material Development and Strain Capacity of Grade X100 High Strain Linepipe Produced by Heat Treatment Online Process," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

18 Wang, Y.-Y., Liu, M., Stephens, M., Petersen, R., and Horsley, D., "Recent Development in Strain-Based Design in North America," Proceedings of the 19th International Offshore and Polar Engineering Conference (ISOPE 2009), Osaka, Japan, July 21-26, 2009.

19 Duan, D., Zhou, J., Rothwell, B., Horsley, D. and Pussegoda, N., "Strain aging effects in high strength line pipe materials," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

20 Denys, R., Lefevre, A., De Baets, P., and Degrieck, J., "Effects of Stable Ductile Crack Growth on Plastic Collapse Defect Assessment," Proceedings of the Third International Pipeline Technology Conference, Brugge, Belgium, May 21-24, 2000, Vol. 1 pp.169-189.

21 Liu, M. and Wang, Y.-Y., "Advanced Modeling of Plasticity of Linepipe Steels with Anisotropic Texture and Complex Loading History," Proceedings of the Seventeenth International Offshore and Polar Engineering Conference (ISOPE 2007), Paper No. 2007-SBD-12, Lisbon, Portugal, July 1-6, 2007.

22 Tsuru, E., Yoshida, K., Shirakami, S. and Kuwabara, T., " Numerical Simulation of Buckling Resistance for UOE Line Pipes with Orthogonal Anisotropic Hardening Behavior", Proceedings of the Eighteenth International Offshore and Polar Engineering Conference (ISOPE 2008), Vancouver, British Columbia, Canada, July 6 – 11, 2008.

23 Bruschi, R., Bartolini, L., Spinazze, M., Torselletti, E., Vitali, L., "A Numerical Lab to Predict the Strength Capacity of Offshore Pipelines", Proceedings of 24th International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2005), June 12-17, Halkidiki, Greece, 2005.

24 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," 26th International Conference on Offshore Mechanics and Arctic Engineering, OMAE2007-29415, San Diego, June 10-15, 2007.

25 Tsuru, E., Shinohara, Y, Asahi, H, and Terada, Y, "Strain capacity of line pipe with yield point elongation." Proceedings of the Fifteenth International Offshore and Polar Engineering Conference", Seoul, Korea, June 19-24, 2005.

26 Column Research Council, 1966.

27 Stephens, DR, Olson, RJ, and Rosenfeld, MJ (1991). "Topical report on pipeline monitoring – Limit state criteria." NG-18 report No. 188, Battelle, Columbus, OH, USA.

28 Wang, Y.-Y., Liu, M., "Weld Integrity of High Strength Pipelines: From Construction to In-service Large Displacement Loading", Proceedings of X80 & HGLPS 2008: International Seminar on X80 and Higher Grade Pipe Line Steel, Xi'an, China, June 23-24, 2008.

29 Yatabe, H., Fukuda, N., Masuda, T. and Toyota, M., "Application of X80 in Japan: Earthquake Resistance", 4th International Conference on Pipeline Technology, May 9-13, 2004, Ostend, Belgium.

30 Glover, A., Zhou, J., Horsley, D., Suzuki, N., Endo, S. and Takehara, J., "Design Application and Installation of an X100 Pipeline," Proceedings of 22nd International Conference on Offshore Mechanics and Arctic Engineering, Paper No. OMAE2003-37429, Cancun, Mexico, 2003.

31 Glover, A., Horsley, D., Dorling, D. and Takehara, J., "Construction and Installation of X100 Pipelines," Proceedings of the 5th International Pipeline Conference, Paper No. IPC04-0328, Calgary, Canada, 2004.

32 Ishikawa, N., Okatsu, M., Endo, S., Kondo, J., Zhou, J. and Taylor, D. "Mass Production and Installation of X100 Pipeline for Strain-Based Design Application," Proceedings of 7th International Pipeline Conference (IPC2008), September 29-October 3, 2008, Calgary, Alberta, Canada.

33 "Steel Pipe," CSA Z245.1-02, Canadian Standards Association, Mississauga, ON, Canada, 2002.