Fracture resistance against internal pressure on high strength over X80 line pipe

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ABSTRACT

The demand for natural gas is growing worldwide. X80 and lower grade line pipe has been already used for pipeline. Now X100 and X120 line pipe steel is under developing for the next-generation line pipe steel. However, any specifications were not intended to X120. Taking the safety operation into account, the evaluation of yield strength is the basic parameter. Because the design pressure in most pipelines is allowed as high as 80% of the Specified Minimum Yield Stress (SMYS) by many pipe line codes. Small-scale testing including round bar and strap specimen, ring expansion testing, and hydrostatic burst test were conducted. This paper presents the characteristic of deformability against internal pressure especially on high strength over X80 line pipe. Results from our studies showed that keeping the required YS and TS on round bar specimen and TS on welded joint is the guarantee of the pipe fracture resistance against internal pressure, in addition, X100 steel could be designed to the same fraction of the SMYS as lower-grade line pipe.

KEYWORDS

high strength, longitudinal seam submerged-arc welded pipe, tensile properties, small-scale test, Ring Expansion test, burst test

INTRODUCTION

Natural gas demand as the primary sources of energy is increasing, and economic analysis indicates that using high-strength line pipe has significant economic advantages.

At present, X80 and lower grade is general grade for the pipeline application. These days, many studies for X100 and X120 grade steel are reported. [1-8] In addition to those studies, the work for standardization of such high strength steel as international specification, API and ISO is being continued.

The other important key for commercializing high-strength steel is no reduction for safety operation comparing to the conventional grade steel. For conventional grade steel, API and ISO specify the yield and tensile stress of hoop pipe body and the tensile strength on welded joint tensile test as the representative value for pipe properties. Then, line pipe has been operated safely. Technical papers about high-strength steel resulted that the tensile properties over X80 grade are not the same as the conventional steel. [1-8]

For the safely application of such high-strength steel, the following three points should be investigated

1) The Guarantee of yield stress against internal pressure
2) The Guarantee of strain capacity against large longitudinal deformation [9]
3) The Guarantee of the fracture arrest ability [10,11]

In addition, field weldability is another key for the application; some studies reported that it is possible to keep mechanical properties and to perform the welding economically. [12]

The yield stress against internal pressure is focused and verified in this paper. Small-scale tensile tests, ring expansion test, and hydrostatic burst test were conducted to ensure the tensile properties of high strength line pipe steel against internal pressure.

1. TEST MATERIALS AND TEST METHODS

For evaluating the yield stress against internal pressure, 4 SAW pipes, X60, X70, X80 and X100 grade steel pipes were chosen. Chemistries, pipe size and microstructures on each material are summarized in Table 1. Basic oxygen furnace, continuous casting and TMCP were applied for all materials. To achieve optimum microstructures, the rolling and cooling condition were carefully selected. For pipe making, the UOE process was applied. The UOE process is the common manufacturing process for high-strength large-diameter pipes for gas transmission pipelines. In this process, the cold working (bending, squeezing and expanding) is controlled at each step so as to achieve precise dimensions and properties. Plates applied for UOE process are designed, after knowing the change of properties caused by the cold working and the property of the Heat Affected Zone (HAZ) created by SAW seam weld. Taking the cold deformation influences on mechanical properties into account, t/D (thickness/ Diameter (%)) is restricted between 2.1 and 2.7.

In this paper, in addition to the small-scale tensile testing such as round bar and strip specimen, ring expansion and hydrostatic burst test were conducted. In case of high strength SAW line pipe such as X100, it is reported that as the HAZ softening becomes larger, overmatching (=strength on weld metal / strength on weld metal) becomes smaller, it is not always the case the joint strength exceeds the base metal strength, and fracture occurs in base metal. Ring expansion test is used for the evaluation of the tensile properties on each position. To investigate the tensile properties on seam weld, HAZ and base metal, strain gages were placed respectively. Hydrostatic burst test was also performed on X65 and X100 SAW 3m length pipes. Both specimens were instrumented with strain gages placed on weld, HAZ and base metal, as well as ring expansion, to capture the response of the materials as internal pressure was applied. The pressure was gradually increased using a high-pressure water pump. In case of ring expansion test, water pressurizing was kept until the total circumferential elongation reached 0.5% to investigate yield strength of the tested pipe. Otherwise, hydrostatic burst test is the test to evaluate the burst pressure and the crack initiation position, and then water pressurizing was continued until the tested pipe burst.

Comparing and verifying these three tests leads the appropriate evaluation method for the deformability on high-strength line pipe steel by internal pressure.

Table 1. Test Materials

Material	A	B	C	D
API Grade	X60	X70	X80	X100
Size	914mmOD 25.4mmWT	1016mmOD 21.0mmWT	1066.8mmOD 25.0mmWT	914.4mmOD 19.05mmWT
T/D(%)	2.7	2.1	2.3	2.1
Chemicals	.08C-1.5Mn-Nb-V	.06C-1.6Mn-Cu-Ni-Mo-Nb-V	.07C-1.8Mn-Cu-Ni-Mo-Nb	.06C-1.85Mn-Cu-Ni-Mo-Nb
Ceq(%)1)	.37	.38	.44	.48
Pcm(%)2)	.16	.17	.19	.20
Plate Rolling	TMCP	TMCP	TMCP	TMCP
Microstructure3)	F+P	AF	AF	LB+M
Pipe Making process	UOE	UOE	UOE	UOE

1) Ceq(%)= C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15

2) Pcm (%) = C+Si/30+Ni/60+Mo/15+(Cr+Mn+Cu)/20+V/10+5B

3) F: Ferrite P: Pearlite, AF: Acicular Ferrite, LB: Lower Bainite, M:Martensite

2. TEST RESULTS

2-1. Small-scale tensile test results

Small-scale tensile testing as strip or round bar specimen is generally used for evaluating a pipe's base metal tensile property. This test is very easy to conduct. Small –scale test results were summarized in Table2. Tensile Strength (TS) on both methods are almost the same, but the difference of measured Yield Stress (YS) between API strip specimen and round bar specimen became larger as the grades became higher. (See Section 2-1-1) In addition, generally, YS is defined as the stress corresponding to 0.2% offset and or 0.5% total strain. The difference between them was discussed at Section 2-1-2.

Table 2 small-scale test results on circumferential direction (MPa)

Specimen / Sample	API strip specimen			Round bar specimen		
	0.2% Offset-YS	0.5%YS	TS	0.2% offset-YS	0.5%YS	TS
A	-	479	578	493	495	574
B	-	551	629	553	550	623
C	-	583	678	611	603	684
D	-	668	829	809	807	839

2-1-1. Comparison of strip and round bar specimen

Small-scale testing as strip or round bar specimen is generally used for evaluating a pipe's base metal tensile property. The degree of the cold forming may influence the mechanical properties, in these test, t/D ratio was limited between 1.6-2.3%. Full-thickness tensile strip specimen shows the real tensile strength of the pipe, otherwise the measured yield stress cannot be accurate value because the pipe's curvature must be removed from the specimen prior to testing. This effect caused by this flattening process becomes more significant for higher-strength pipe as shown in Fig.1. It is assumed that the S-S curve's changes corresponding to the strength influences this tendency.

This changes is known as the Bauschinger effect. On the contrary, measured YS shows true value as the round bar specimen was not flattened. The specimen extracted from mid-wall thickness is the weak point. The tendency on longitudinal direction is not the same as the transverse results. (Fig.2) In case of longitudinal direction, as flattening process was not applied to both strip and round bar specimen, measured YS and TS is almost same even though the strength level became high.

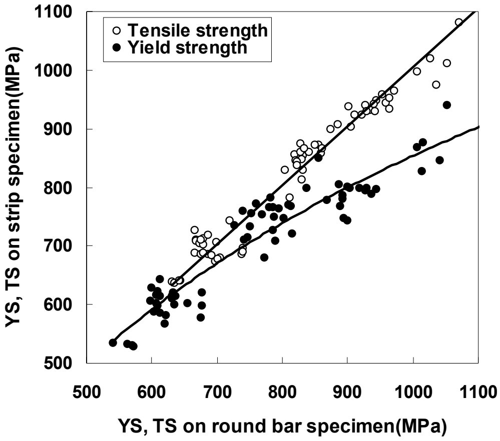

Fig.1 Comparison of **transverse** YS, TS on strip and round bar specimen

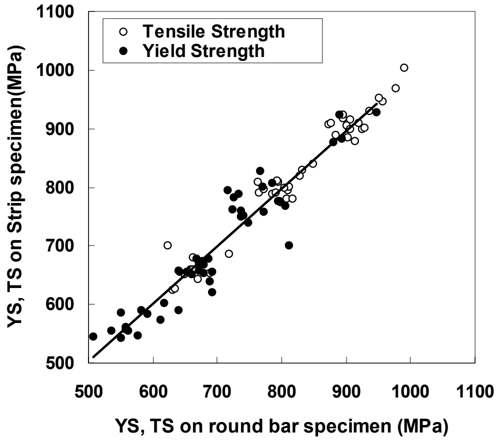

Fig.2 Comparison of **longitudinal** YS, TS on strip and round bar specimen

2-1-2. Definition of YS

YS is now defined as the stress on 0.2% offset and or 0.5% total strain. These two defined values are quite same in X80 and lower grades. On an industrial basis, to measure 0.5% total YS is feasible in terms of cost and time. Otherwise, in case of X100 and higher grades, because of the increase of the elastic region, those two values became apart as shown in Fig.3 and Table3. In case of adopting total strain, for higher grades, it is needed to change the equivalent total strain value. This method is applied for OCTG specified by API5CT. [13]

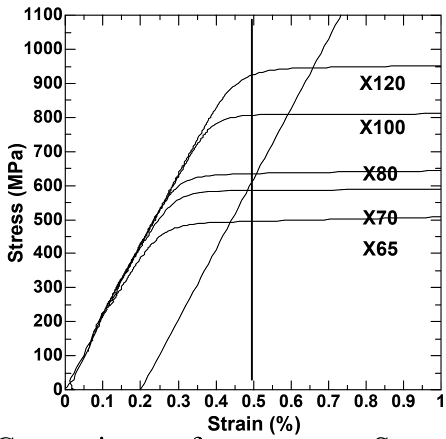

Fig.3 Comparison of transverse Stress-Strain curves

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Table3.　Comparison of YS measured on two methods corresponding to API Grades

	Corresponding total strain showing same stress as 0.2% off-set Stress
X80	0.5%
X100	0.55-0.65%
X120	0.60-0.70%

This tendency results in that 0.2%off-set method is more adequate for measuring YS especially in higher-strength pipes. To adopt this method means the clear definition of YS in spite of the strength changes.

2-2. Welded joint tensile test results

Welded joint tensile tests were performed in order to ensure the joint tensile strength and the fracture position. Test results are summarized in Table 4. In case of X80 and lower grades, the welded joint strength were higher than the TS of the base metal. Failure occurred in base metal because the seam welds were slightly overmatched. Otherwise, in X100, the welded joint TS was almost the same as TS of base metal, and failure location was HAZ. The value could exceed the minimum requirement of X100. It is assumed that the even-matched and HAZ softening caused this. Joint efficiency is the parameter defined as TS on welded joint / TS on base metal. Join efficiency tends to decrease to 1.0 as pipe grades become higher.

Table 4 . Welded joint tensile test results

	welded joint*1)			base metal*2)
	TS (MPa)	Failure location	Joint Efficiency*3)	TS (MPa)
A	613	B.M.	1.07	574
B	648	B.M.	1.04	623
C	726	B.M.	1.06	684
D	838	HAZ	1.01	839

*1) API Strip Specimen　*2) round bar specimen

*3) Joint efficiency = TS on welded joint / TS on base metal

In X100, Low-C steel was used to keep Pcm value as low as possible, and to increase the Charpy absorbed energy for the arrestability of a dynamic ductile fracture. Low Pcm causes HAZ softening. Furthermore, as high toughness is required in weld metal, it becomes difficult to control overmatching as to keep the toughness of weld metal. It is reported that both matching ratio and HAZ softening causing the strain concentration at HAZ control failure location and TS on welded joint.[13]

Especially in case of this X100, it seemed that yield behavior is associated with that of welded joint. To investigate the HAZ yield properties is the key for ensuring the pipe yield phenomena.

In addition, controlling the matching ratio and HAZ softening is important for fracture location, SMI developed the new X100 pipe with high Ceq in purpose of decreasing HAZ softening. [14]

2-2. Ring expansion test results

The specimen used to evaluate the yield behavior of the pipe consisted of 76mm of X60, X70, X80 and X100 pipe. It is reported that in case of X120 burst testing, the pipe body undergoes a little plastic strain before failure, otherwise the strain localizes to the HAZ, and failure subsequently occurs. To evaluate test materials' yield behavior, each specimen was instrumented with strain gages placed on seam weld, HAZ and the base metal. In addition, circumferential changes were measured by steel wire as shown in Fig.4. This test was conducted according to the test standards TM1, adopted by Transco for pipe material test ring. Water pressurizing was stopped when the total circumferential strain reached just over 0.5%.

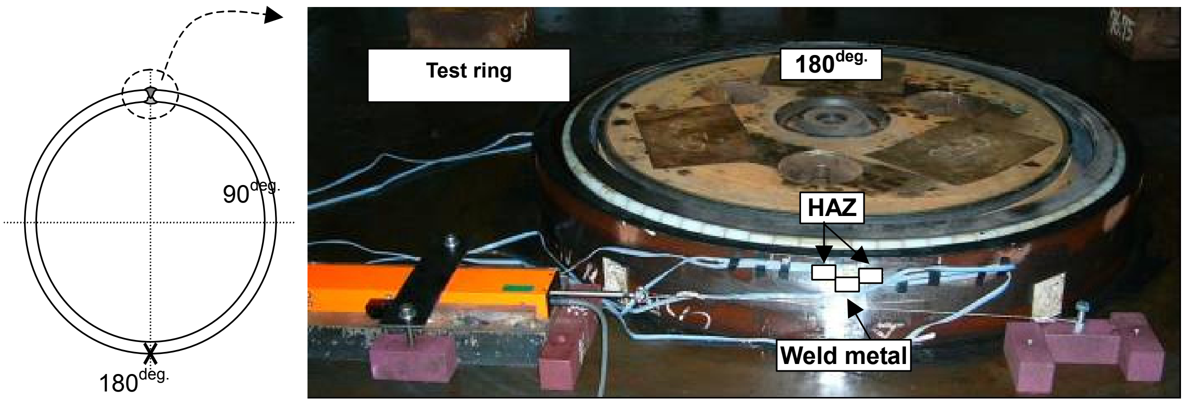

Fig.4 Measuring location for ring expansion test

Fig.5, 6 shows the Stress-Strain curve of X60 and X100 measured by strain gage at HAZ location respectively. Table 4 shows the results of the ring expansion test. This results showed, in all test materials, that YS measured by circumferential strain in this ring expansion test is sufficient high comparing with YS measured on transverse base metal by using round bar specimen. HAZ yield behavior is summarized in Table5. YS measured at HAZ location were always lower than YS of circumferential results. The difference of YS between HAZ and circumferential data becomes slightly higher in case X100. In case of X60, weld, HAZ and base metal began to yield almost simultaneously. Weld and HAZ became to yield firstly in case of X100. Besides, in this X100 ring expansion testing base metal didn't yield.

The most significant result is measured YS at HAZ location in ring expansion test is always the same or higher than the YS measured on transverse base metal using round bar specimen in all materials.

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Table 4. Ring expansion test results (Circumferential changes)

	Ring expansion (Circumferential strain wire)		Transverse base metal (Round bar specimen)	
	0.2%0ffsetYS (MPa)	0.5%YS (MPa)	0.2%0ffsetYS (MPa)	0.5%YS (MPa)
A	558	565	493	495
B	614	610	553	550
C	649	648	611	603
D	851	849	809	807

Table 5. Ring expansion test results (HAZ measured by strain gage)

	Ring Expansion (HAZ strain gage)		Transverse base metal (Round bar specimen)	SMYS (MPa)
	0.2%0ffsetYS (MPa)	0.5%YS (MPa)	0.2%0ffsetYS (MPa)	
A	536	538	493	414
B	606	604	553	485
C	637	634	611	551
D	812	809	809	689

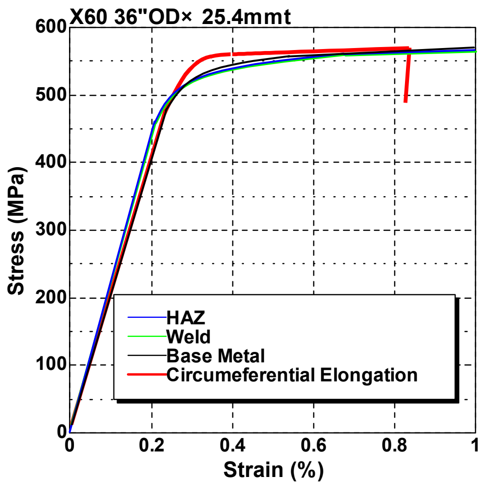


Fig.5 Stress-Strain curve in X60 ring expansion test

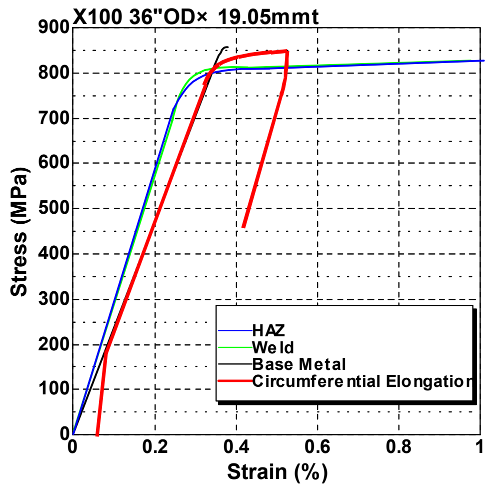
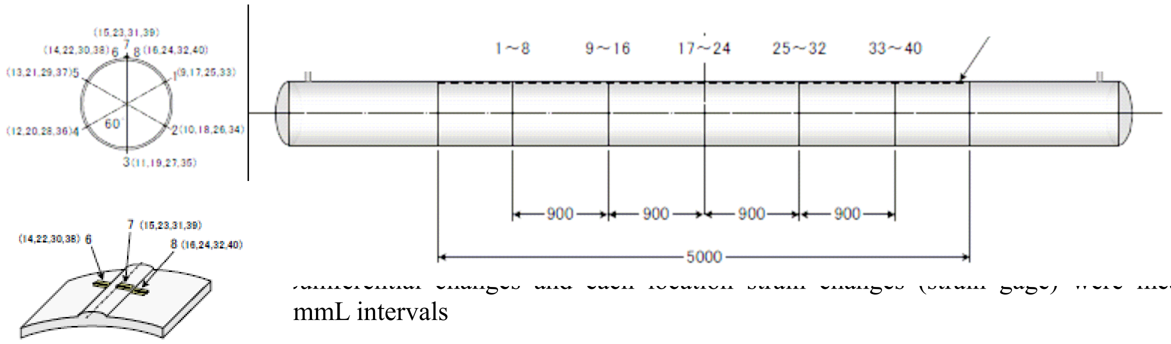


Fig.6 Stress-Strain curve in X100 ring expansion test

2-3. Hydrostatic burst test results

X60 and X100 pipes were used for hydrostatic burst test. Test specimens used to evaluate the burst capacity of the pipe consisted of approximately 5m with specially designed, high-pressure end caps welded onto each end. Strain gages were placed on the seam weld, HAZ and base metal. Measuring position is shown in Fig.7. YS of localized zone such as HAZ or Weld was defined by the data using 5mm strain gages. As shown in this figure, strain gages were attached on the outside surface of the pipe. Before testing, test specimen was filled with water. The pressure was increased gradually by using high-pressure pump until the test specimen reached to fracture.



... at mmL intervals

Fig. 7 Measuring position in hydrostatic burst test

Table6 shows the results of burst test. Failure locations were base metal in X60, HAZ in X100, respectively. These results were as same as welded joint test as shown in Table 4. Fracture manner were ductile in both cases. TS of hydrostatic burst test in X60 was almost same as TS of base metal obtained from round bar specimen, otherwise, in X100 TS of hydrostatic burst was almost same as TS of welded joint. This results shows that according to the welded joint test results, ultimate TS of the pipe could be predicted.

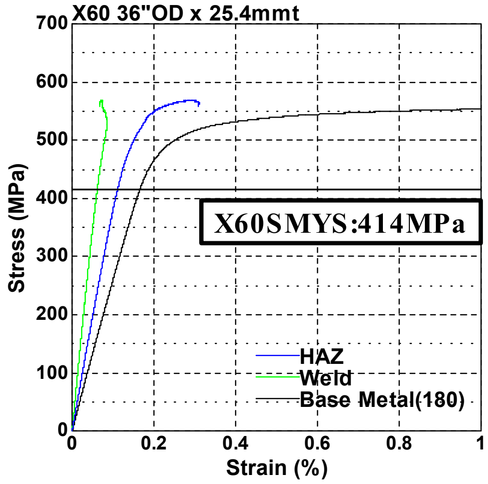
YS at HAZ location was summarized in Table 7. Stress-strain diagrams of X60 and X100 at weld metal, HAZ, and base metal measured by strain gages were shown in Fig.8 and Fig.9 respectively. These data shown in Fig.7 and Fig.8 were used the data near the location failure initiated. In case of X60, HAZ yielded firstly, then base metal yielded. Finally pipe was fractured at base metal 180 degree away from weld seam. In X100, HAZ and weld yielded firstly, in this hydrostatic test, base metal yielded before fracture. From these results, it was clear that YS on HAZ were higher than YS on base metal measured by round bar specimen as well as ring expansion test.

Table 6. Hydrostatic burst test results

	Hydrostatic burst test		Small-scale test	
	TS (MPa)	Failure location	Round bar-TS (MPa)	Welded joint TS (MPa)
A	578	Base Metal	582	613
D	841	HAZ	840	838

Table 7. Hydrostatic burst test results

	Hydrostatic burst test (HAZ)		Small-scale test (round bar)	
	0.2%0ffsetYS (MPa)	0.5%YS (MPa)	0.2%0ffsetYS (MPa)	0.5%YS (MPa)
A	-	-	493	495
D	823	822	809	807



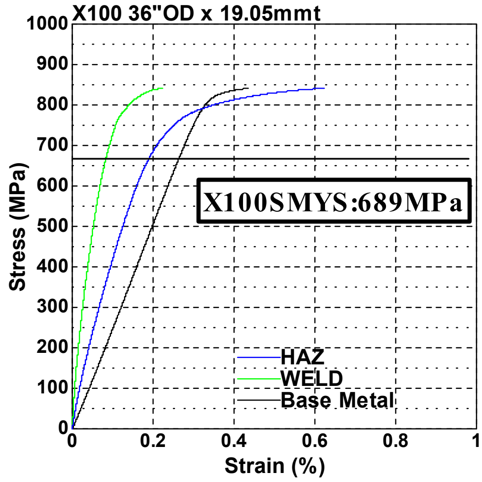


Fig.8 Stress-Strain curve in X60 hydrostatic burst test

Fig.9 Stress-Strain curve in X100 hydrostatic burst test

3. Discussion

The results from these tests showed that YS and TS of small-scale tensile test could be representative values of pipe under condition that the overmatching and HAZ softening were controlled in appropriate range.

Tensile Strength

As indicated in Table 6, in case of the base metal fracture occurs on welded joint tensile test such as X60, ultimate TS of pipe was almost same as TS on base metal measured by round bar specimen.

X100 test results showed that despite failure occurring at HAZ, TS on hydrostatic burst test is sufficient higher than required TS, and also was as same as TS on welded joint.

From these studies, X60 and X100 had sufficient tensile strength in both base metal and welded portion against internal pressure. To keep the required TS on small-scale testing is the guarantee of the pipe ultimate TS in X60 to X100 pipes. In addition, it was reported X120 has also sufficient tensile strength above SMTS, despite failure occurring HAZ as same as X100 pipe. [6,7]

Yield strength

To ensure the yield strength of the pipe, round bar, ring expansion, and hydrostatic burst test were performed. The results from small-scale testing showed that 0.2% off-set YS is the appropriate value for the YS on base metal. Yield behavior at HAZ position were measured in ring expansion test and hydrostatic burst test by using strain gages. In case of X60, X70 and X80, as failure locations on welded joint test were base metal, YS of the pipe could be simulated by the 0.2% YS of base metal using round bar specimen.

HOME

On the other hand, in case X100, failure location at welded joint test and hydrostatic burst test were HAZ. 0.2% YS of base metal using round bar specimen could not be the representative value for the YS of X100 Pipe. Although, as shown in Fig.10, the value of measured YS divided by the welded joint TS were 0.97 in ring expansion test and 0.98 in hydrostatic burst test, respectively.
This value means that as long as the pipe has sufficient TS above SMTS, HAZ could keep SMYS
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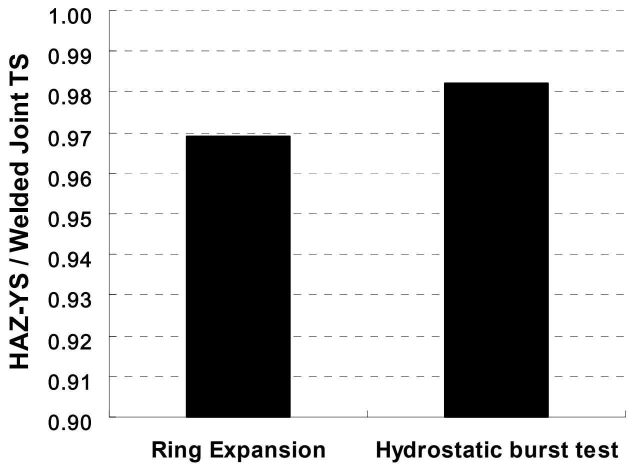

Fig.10 YR at HAZ location

Results from these studies showed that keeping the required YS and TS on round bar specimen and TS on welded joint is the guarantee of the pipe fracture resistance against internal pressure.
X100 pipe could be designed for pipeline as same as lower grade pipes, as long as keeping 0.2% offset YS on round bar at base metal and TS on welded joint.

4. Conclusion

- 0.2% offset YS value of round bar could be used for the YS of the pipe in all grades.
- 0.2% offset YS values on ring expansion test against internal pressure are always above the 0.2% offset YS value on base metal using round bar.
- In X100, strain localization occurres at HAZ location because of HAZ softening and low matching ratio, and volume fraction change in hydrostatic burst test becomes smaller comparing with conventional grade steel.
- As long as TS on welded joint meets the SMTS, burst stress and YS on HAZ location against internal pressure could keep the SMTS and SMYS in hydrostatic burst test.
- X100 pipe could be designed for pipeline as same as lower grade pipes, as long as keeping 0.2% offset YS on round bar at base metal and TS on welded joint.

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