NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 107 FEBRUARY 2015

Technical Report

UDC 669 . 14 . 018 . 295 - 462 . 3 : 621 . 791 . 75

Development of X90-X100 Seamless Line Pipes and Their Application

Yuji ARAI*
Jun NAKAMURA
Kunio KONDO
Nobuyuki HISAMUNE
Hiroyuki NAGAYAMA
Masahiko HAMADA
Hiroyuki HIRATA
Tsuneo MURASE

Abstract

With the increasing strong demand for the development of oil and gas fields in ultra-deepwater, offshore applications with higher strength are required. In addition, fatigue properties of parent pipe and welding joints are required for riser systems as cyclic stress is applied marine phenomena. Ultra-high strength seamless pipes of X90 and X100 grades have been developed for deepwater or ultra-deepwater applications. In order to assess the applicability of X90 parent pipe and welded joints for riser applications, high cycle fatigue testing and fatigue crack growth rate testing was conducted. This work was performed with Engineering Critical Assessment (ECA) for riser applications by using the material and fatigue properties of X90 parent pipe and welded joints.

1. Introduction

As an increasing number of oil and gas fields are developing deep underwater over recent years, the order acceptance has been increasing for high-strength, thick-wall seamless steel pipes for line pipe use. Oil and gas from an underwater field is brought from a wellhead on the seabed to the exploration platform above the water through pipelines called flow lines and riser pipes. The steel pipes used for these applications are subjected to high pressure by the fluid inside, and accordingly higher strength is required for them as the need increases for development at greater depths, pipe laying at lower costs, and operating the lines at higher pressures for higher production efficiency.

According to conventional standards applicable to seamless line pipes, such as 5L of the American Petroleum Institute (API), the highest grade in terms of strength is X80, where the lower limit of yield strength is 555 MPa (unless otherwise specified, the units herein used are metric), and there have been very few cases where pipes of higher strengths are commercially used. The toughness of parent pipes and girth weld joints generally tends to decrease as the material strength increases, and therefore a new steel material has to be developed to further increase the strength and toughness of parent pipes, and at the same time, improve the workability at girth welding. Top tension risers (TTR), which connect a wellhead to a production platform, encase and protect the tubing through which the oil and gas flows, and thus the pipes used for TTR must have good fatigue properties to withstand the vibration caused by waves and tides.

This paper reports the material design in the development of a new, highly weldable seamless pipe product having unprecedented strength equivalent to the API X90 to X100 grades, the results of property evaluation of the product that was trial produced on a commercial mill, and the results of the reliability assessment of the parent pipes and welded joints through fatigue test and engineering critical assessment (ECA).

2. Development of Steel

API X70 seamless pipes, the strongest line pipes available, are made of steel containing approximately 0.1% C, from 1 to 1.75% Mn, and alloying elements, such as Cr, Mo, Ni, and Cu, by small amounts (the percentages of component elements are in mass), and having a carbon equivalent of 0.42 or less according to the Ceq formula or 0.23 or less according to the Pcm formula. In addition, the steel contains microalloys such as Ti, Nb, and V, and the product pipes are quenched and tempered (QT) after rolling. With this steel

---

* Senior Researcher, Pipe & Tube Research Lab., Steel Research Laboratories
1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891

chemistry, however, it is difficult to attain the target strength and toughness exceeding those of X90. Therefore, to examine the effects of steel chemistry over strength and toughness, the authors melted different steels (containing between 0.04 and 0.07% C, between 1.4 and 2.9% Mn, 0.7% or less Cu, 0.9% or less Ni, 0.7% or less Cr, and 0.8% or less Mo) in the laboratory, and rolled the steels into plates 20 mm in thickness using laboratory equipment for hot rolling and QT; this equipment was designed to simulate the company's commercial in-line QT equipment[1] for line pipe production. Using the plate specimens thus prepared, they studied the combined effects of the carbon equivalent (Pcm) and the content of a microalloy element (V) over strength and toughness.

Figure 1 shows the relationship between the yield strength and the Pcm of the specimens. The graph shows that the strength of X90 or higher is obtainable by increasing the content of C and adding V, even when Pcm is low. When V is not added, the desired strength can still be reached by increasing Pcm. On the other hand, as seen in **Fig. 2**, it is clear that the energy transition temperature at Charpy V-notch (CVN) test, an indicator of low-temperature toughness, decreases by increasing Pcm. In addition, it became clear that increasing the contents of Mn and Mo was effective at lowering the transition temperature. This is presumably because Mn and Mo have stronger effects than other alloying elements to lower the transformation temperature during quenching[2] and make the structure homogeneous and fine. Therefore, it seemed promising to attain both the target strength and toughness in the Pcm range of 0.25 or less. Further, the authors confirmed through taper hardness test (according to JIS Z 3115) and synthetic thermal cycle test that, even when Pcm was unchanged, excessive hardening of the heat affected zones (HAZ) of a welded joint could be avoided (see **Fig. 3**), and their toughness would increase (see **Fig. 4**) by lowering the C content and increasing the Mn content.

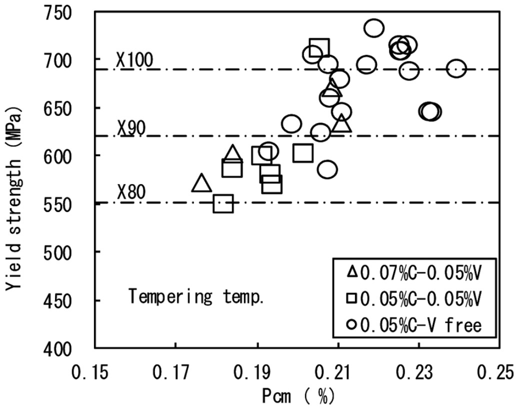

Fig. 1 Effect of Pcm on yield strength of simulated inline QT steel plate (tensile test in L direction)

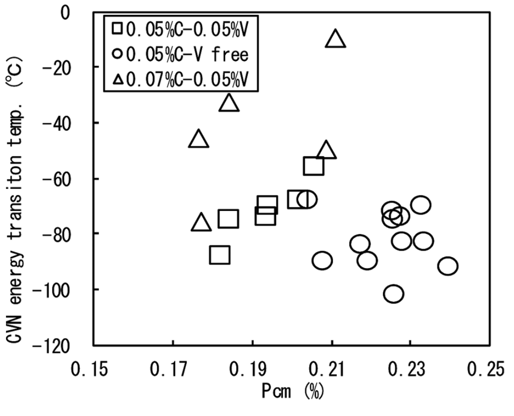

Fig. 2 Effect of C content, V addition and Pcm on energy transition temperature of simulated inline QT steel plate (CVN test in T direction)

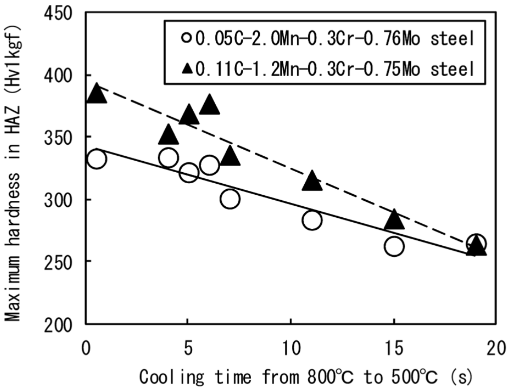

Fig. 3 Relationship between cooling time from 800°C to 500°C and maximum hardness in HAZ bead on plate test

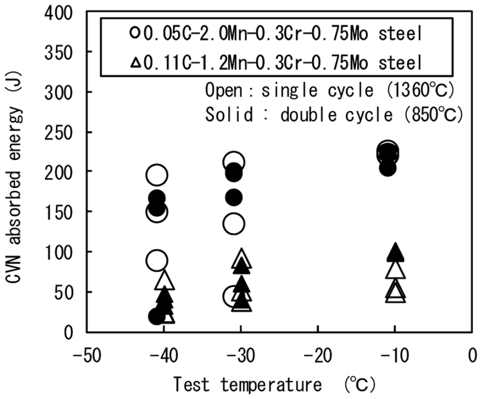

Fig. 4 Comparison of simulated HAZ toughness between 0.05%C-2.0%Mn steel and 0.11%C-1.2%Mn steel

3. Properties of Pipes Trial-produced on a Commercial Mill

Based on the alloy design explained above, steel pipes of the chemical composition shown in **Table 1** were rolled for trial purposes at Medium-diameter Seamless Pipe Mill Plant of Wakayama Works. Some of the pipes (20 mm in wall thickness) went to the in-line QT process directly after rolling, and the rest (25 mm in wall thickness) were left to cool to room temperature after rolling and then reheated for off-line QT. **Photo 1** shows a typical microstructure at the thickness center of an as-quenched pipe taken through a transmission electron microscope; the structure is mainly composed of homogeneous bainite. The material strength was made different, to the levels of X90 and X100, by changing the tempering condition, and their properties were evaluated. The mechanical properties of the trial-produced pipes are given in **Table 2**; all the specimens exhibited excellent low-temperature toughness.

The pipes were subjected to a girth-welding test: the X90 pipes

Table 1 Chemical compositions of developed pipes

(mass%)

C	Si	Mn	Cr	Mo	Others	Pcm
0.04 - 0.06	0.30	2.1	0.3	0.7	Ti,Ca,Al etc.	0.22 0.24

Tabla 3 CTOD test results in welded portion of X100 seamless pipe

	Weld metal	FL	FL+1mm	Visible HAZ
CTOD	0.16	0.33	0.57	0.86
values	0.14	0.47	0.60	0.81
(mm)	0.21	0.50	0.68	0.83

Table 2 Mechanical properties of trial-produced pipes

Grade and size of pipes			Tensile properties					CVN properties
Grade	OD (mm)	WT (mm)	Direction [*1]	YS (MPa)	TS (MPa)	YS/TS (%)	Elongation (%)	vE-20°C (J)
X90	323.9	20	L	664	730	91	42	-
			T	664	727	91	25	258
X100	323.9	20	L	719	822	87	40	-
			T	737	832	89	21	185
X100	323.9	25	L	750	812	92	45	-
			T	735	798	92	23	269

*1 L: Longitudinal direction, T: Transverse direction

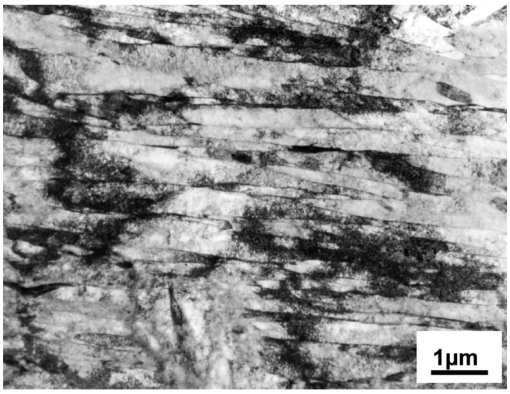

Photo 1 TEM image at mid-wall of quenched pipe

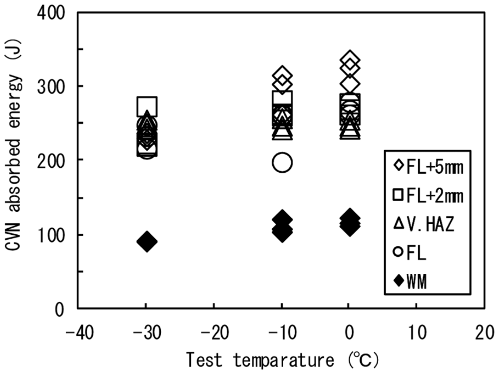

Fig. 5 CVN test results of welded joints of X100 seamless pipe

were welded under conditions specified for riser pipes (to be explained later in detail), and the X100 pipes under typical conditions simulating the welding of flow lines: U grooves, gas metal arc welding without pre-heating and with a heat input ranging from 0.5 to 0.9 kJ/mm.

Figure 5 and **Table 3** show the results of CVN test and crack tip opening displacement (CTOD) test of the girth-welded joints of the X100 pipes, respectively. The test pieces were taken in the longitudinal direction from the wall thickness center at the welded joints, and the notch was cut at the weld metal (WM), fusion line (FL), between 1 and 5 mm from the FL (FL + 1 to 5 mm), or the visible HAZ (V. HAZ). The CVN absorbed energy at −30°C was 100 J or more, and the CTOD value at 0°C exceeded 0.3 mm with all test pieces. These results indicate that the trial-produced pipes cleared the lower limit figures for Grade 555 under DNV-OS-F101 of the Norwegian Classification Society Standards (equivalent to API X80QO), which evidences excellent toughness of the girth-welded joints of the developed pipes.

4. Properties of Girth-welded Joints of X90 Pipes for TTR and Fracture Safety Evaluation

4.1 Girth welding method for TTR

Test was conducted using the X90 seamless pipes, 323.9 mm in outer diameter and 20.0 mm in wall thickness, trial produced at Wakayama Works.

The specimen pipes were girth welded at RTI Energy Systems, USA, a major riser manufacturer. To simulate the conditions of actual TTR manufacturing, a whole set of the welding facilities of RTI were used for the test under the same conditions as those in field practice. Pipe ends were cut into the shape of weld grooves, and pipes were joined through multipass submerged arc welding (SAW), the main welding process for assembling risers.

Table 4 shows the procedure of the girth welding in detail: the root and second passes were performed by gas tungsten arc welding (GTAW), and the other passes were performed by SAW using high-strength metal cored wire and high-basicity flux procured in the USA market. All welding passes were performed in the flat position (1G according to ASME) from the outside of the pipes that turned on the surface of rollers.

4.2 Evaluation of joints of X90 pipes girth-welded by SAW

To evaluate the properties of the girth-welded joints, tests were conducted on the tensile strength, Vickers hardness, Charpy absorbed energy, and CTOD of the weld metal. It has to be noted that, in the field risers manufacturing, excess weld metals on the inner and outer surfaces are removed to improve fatigue properties, and accordingly the same effort was taken before the tests.

Table 4 Welding procedures of X90 SAW joints

Pre-heat temp.	Interpass temp.	GTAW for root and hot passes			SAW for fill and cap passes			
		Consumable		Ave. heat input	Consumables			Ave. heat input
		Wire	Wire dia.		Wire	Wire dia.	Flux	
121°C	Max. 260°C	AWS A5.28 ER100S-G	1.0 mm	1.06 kJ/mm	Metal cored	2.4 mm	Fluoride basic flux system	1.22 kJ/mm

Table 5 Results of all-weld-metal tensile test of X90 welded joints

YS (MPa)	TS (MPa)	YS/TS (%)	El (%)
645	786	82	26.8

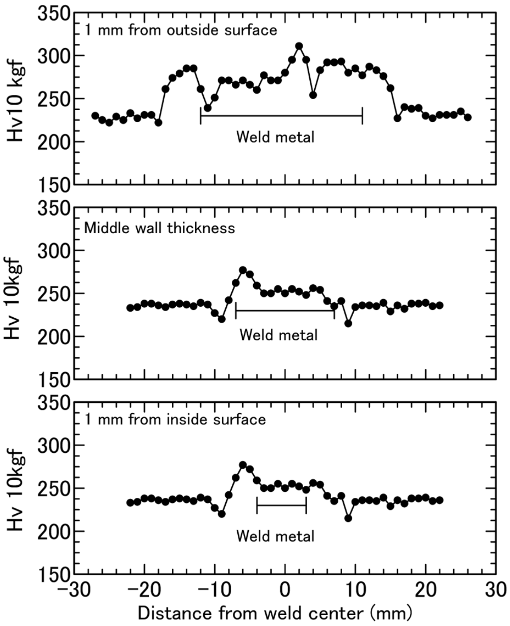

Fig. 6 Hardness distributions of X90 welded joints

For the tensile test of the weld metal, round-bar test pieces 6.4 mm in diameter were cut from the thickness center of the walls such that the parallel portion consisted entirely of the weld metal; the gauge length was 25.4 mm. **Table 5** shows the results of the tensile test. The 0.2% proof and tensile strength of the weld metal were 645 and 786 MPa, respectively; the 0.2% proof stress was greater than 625 MPa, the lower limit yield stress for X90 according to API 5L.

Figure 6 shows the distribution of Vickers hardness across welded joints at a section in the longitudinal direction. The maximum hardness values of the weld metal and HAZ were 311 and 287 HV-10 kgf, respectively, and were recorded 1 mm from the outer surface. This evidences the effects of the low-C, high-Mn steel chemistry to prevent HAZ hardness from excessively increasing.

Tables 6 and **7** show the results of the CVN and CTOD tests of the joints, respectively. The test pieces for these tests were cut in the longitudinal direction, and the notch was cut at the weld metal, FL, and between 2 and 5 mm from the FL (FL + 2 or 5 mm). The test temperature of the CVN test was −20°C and that of the CTOD test was 0°C. The lowest figure of the absorbed energy at the CVN test was 100 J or more with any notch position, and the minimum CTOD value of the HAZ was 0.248 mm with the notch at the FL. This minimum CTOD value was used for the ECA explained herein later.

Table 6 CVN test results of X90 welded joints

CVN absorbed energy, min./ave. (J)				
Notch	Weld metal	FL	FL+2 mm	FL+5 mm
-20°C	100/103	105/114	204/233	218/235

Table 7 CTOD test results of X90 welded joints

CTOD value (specimen thickness: B=16.0 mm, depth: W=2B) (mm)				
Notch	Weld metal	FL	FL+2 mm	FL+5 mm
0°C	0.279	0.588	0.929	1.064
	0.238	0.563	1.006	0.966
	0.289	0.248	0.827	1.025

4.3 Fatigue properties of X90 pipes and welded joints

The steel pipes used for TTR and other types of risers must be resistant to the fatigue caused by the vibrations of waves and tides. In the case of TTR, the stress ratio R ($\sigma_{min}/\sigma_{max}$) is generally known to range from 0.5 to 0.7, and it is necessary to confirm the fatigue properties of the pipes under such stress conditions.

High-cycle fatigue test of the X90 pipes was conducted changing the stress ratio R from −1 to 0.7. **Figure 7** shows a typical relationship between the stress range (the difference between the maximum and the minimum stresses) and the fatigue life of the X90 pipes in normal atmosphere when the stress ratio R is 0.05; unnotched test pieces 8.0 mm in diameter were used for the test. With this stress ratio, the endurance limit is 650 MPa, the stress amplitude σ_a is 325 MPa, and the mean stress σ_m 359 MPa. Likewise, endurance limits were measured under different stress ratios. **Figure 8** shows the relationship between the stress amplitude σ_a and the mean stress σ_m under different values of endurance limit. The graph also shows some models that have been proposed regarding the effects of mean stress over fatigue life.[3-5] Because the endurance limits of X90 pipes under different stress ratios are equal to or better than those defined by the Gerber curve, the severest of endurance limit curves, the fatigue properties of the specimen X90 pipes can be considered excellent.

Figure 9 shows the relationship between the maximum stress and fatigue life of the X90 parent pipes and their welded joints in the atmosphere when the stress ratio R is 0.7. The graph indicates that the endurance limit of the welded joints under this condition is the same as that of the parent pipes, which means that the fatigue properties of the welded joints of the developed pipes are as good as those of the parent pipes.

Figure 10 shows the result of fatigue crack growth test of the welded joints of the developed X90 pipes in the atmosphere and under cathodic protection (CP) in artificial seawater at 5°C. Here the artificial seawater was prepared according to ASTM D 1141;[6] compact tension test pieces were used for the test under either environ-

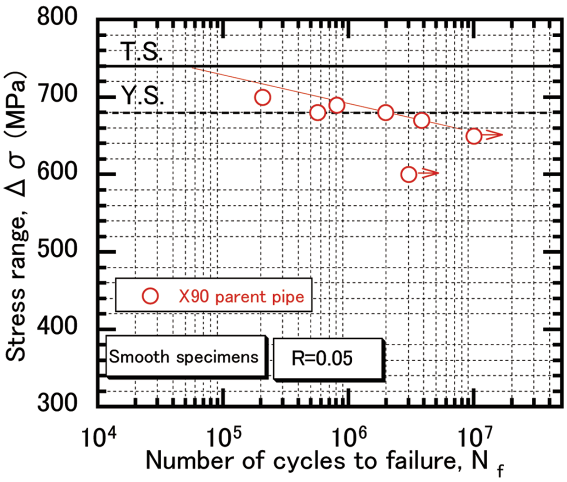

Fig. 7 Relationship between stress range and fatigue life of X90 parent pipe at R=0.05

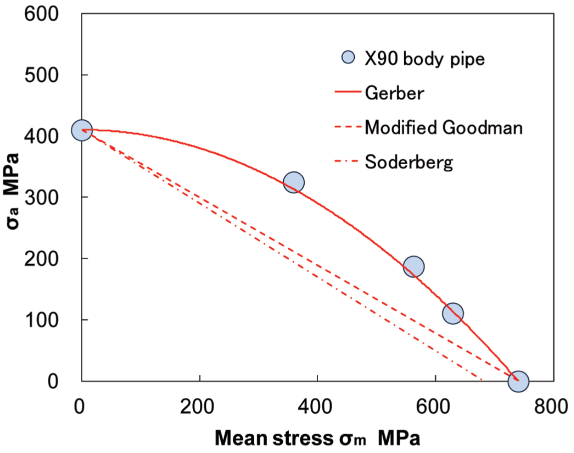

Fig. 8 Endurance limit diagram of X90 parent pipe

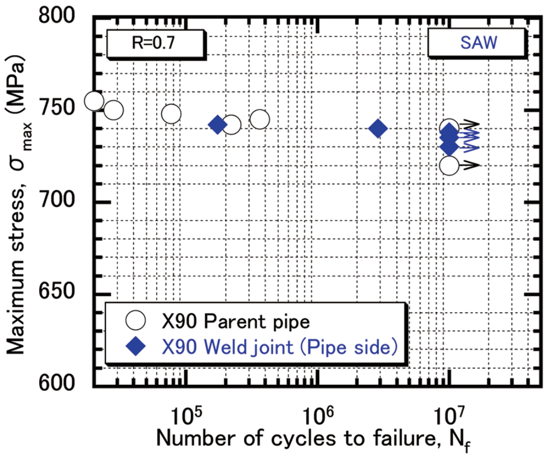

Fig. 9 Relationship between maximum stress and fatigue life of X90 welded joints

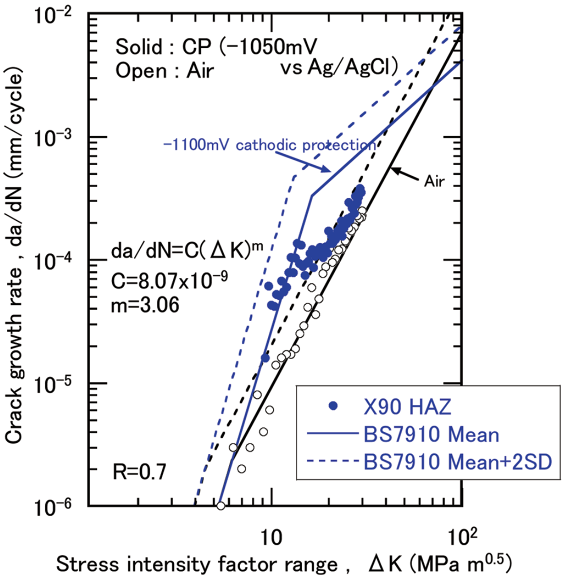

Fig. 10 Fatigue crack growth rate of HAZ (FL) of X90 welded joints

mental condition, the initial crack was given in the HAZ (FL), and the stress ratio R was set at 0.7. It is clear from the graph that the fatigue crack growth rate (da/dN) either in the atmosphere or under CP in the artificial seawater is lower than the design guideline curve plus twice standard deviation (BS 7910 Mean + 2SD, the blue dotted curves) proposed in BS 7910 for both environmental condition.[7] This evidences the excellent fatigue crack growth properties of the HAZ of the X90 pipes. The authors conducted the same test on the parent pipes to confirm that the crack growth rates were below the guidelines specified in BS 7910.[8] From the fatigue crack growth data in the atmosphere of Fig. 10, they calculated the exponents and constants for the Paris law in fatigue crack growth rate and used them in the ECA explained below.

4.4 Engineering critical assessment of welded joints of X90 pipes

ECA is a method for evaluating the soundness of a metal structure, especially a welded structure, having a known flaw. When the size of an initial flaw, the material properties, and load conditions of a welded structure are given, ECA can evaluate the fracture safety of the structure under static and dynamic loads using the failure assessment diagram method. Based on the properties of the girth welds explained earlier, the authors conducted ECA to judge if welded joints of the X90 pipes were good for actual use as risers, or in other words, if the size of an allowable initial flaw was sufficiently large.

CrackWISE® 4, a general-purpose program developed by TWI, was used for the present ECA. For evaluating the soundness of HAZ (FL), the evaluation results of girth welds explained earlier were used as material properties. An initial flaw was supposed at the inner surface in two different shapes given in **Fig. 11**: a local crack and a crack along the entire circumference. The shape of a local crack was defined in terms of its aspect ratio 2c/a (c: crack length, a: crack depth), and the allowable size of a local or circumferential crack under static and dynamic loads was evaluated. The static and dynamic loads were defined in consideration of the stress imposed on a riser pipe during installation and operation, respectively.

Figure 12 shows the allowable flaw size of a welded joint under static load. The graph indicates that a welded joint will not fail during the installation work of a riser if the size of an initial flaw in it falls within the green area marked "acceptable." This means that a

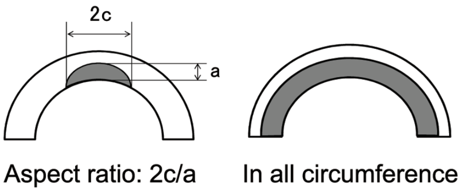

Fig. 11 Schematic illustration of flaw shape

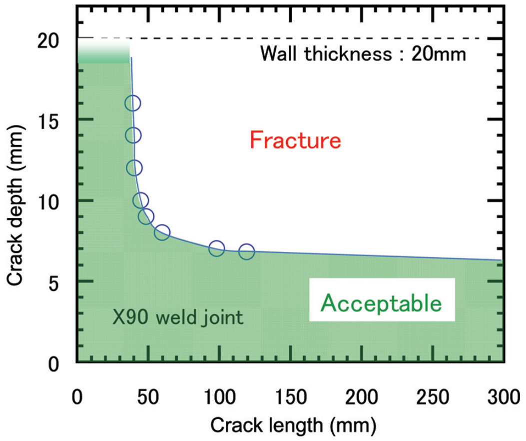

Fig. 12 Allowable critical flaw sizes for the X90 welded joints under static loading conditions

welded joint between X90 pipes will not fail during installation if the depth of the initial flaw is 6 mm or less, regardless of its length. The flaw depth of 6 mm is equal to 30% of the pipe wall thickness, which is easily detectable by ultrasonic test of the welded joint.

With respect to dynamic loads, the fatigue life of the X90 welded joints was evaluated in consideration of the result of the crack growth test on the HAZ explained earlier and assuming different initial flaw sizes. **Figure 13** shows the relationship between the initial flaw size and fatigue life of welded joints under dynamic loads. One can see from the graph that the fatigue life becomes shorter as the aspect ratio of the initial flaw increases (or the crack length increases in relation to its depth). Even in the worst case of a crack covering the entire inner circumference, the joint will not virtually fail to the end of the operation as far as the flaw depth is 2 mm or less. The crack depth of 2 mm is equal to 10% of the pipe wall thickness, which is, again, easily detectable by an ultrasonic test of the welded joint.

The above CEA indicates that the welded joints of the developed X90 seamless pipes are good for practical use as riser pipes under loads expected during installation and operation.

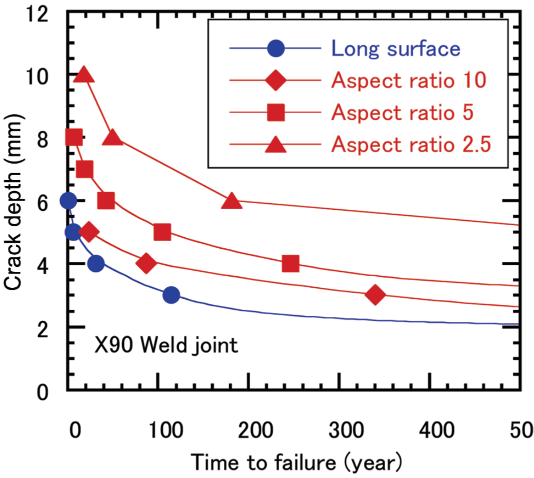

Fig. 13 Relationship between acceptable critical flaw sizes and fatigue life for the X90 welded joints under cyclic loading conditions

5. Closing

Weldable seamless line pipes having unprecedented high strength equivalent to API X90 to X100 have been developed. Thanks to the high strength and toughness of the parent pipes because of appropriate alloy design and the high toughness of welded joints because of reduced carbon content, the developed product is excellent in girth weldability and other performance aspects. Based on the data of trial production, applications for registering the developed pipes in the API standard system were formulated, and they were included in the system as X90Q and X100Q in 2010. The developed pipes demonstrate excellent fatigue properties in either parent pipes or welded joints, and the ECA evaluation result guarantees their performance to fully satisfy the requirements for actual use as the risers for underwater oil/gas development.

References

1) Arai, Y. et al.: International Pipeline Conference. Calgary, 2004, ASME
2) Steven, W., Haynes, A.G.: J. Iron Steel Inst. 183, 349 (1956)
3) Goodman, J.: Mechanics Applied to Engineering. London, Longmans Green, 1899
4) Gerber, W. Z.: Bayer. Arch. Ing. Ver. 6, 101, (1876)
5) Soderberg, C. R., Sweden, V.: ASME Transactions. AER-1S, 52 (1), 1 (1980)
6) ASTM D1141-98: Standard Practice for the Preparation of Substitute Ocean Water. 2008
7) British Standard BS 7910: Guide to Methods for Assessing the Acceptability of Flows in Metallic Structures. British Standard Institution, London, 2005
8) Nagayama, H. et al.: Offshore Technology Conference 2013. Houston


Yuji ARAI
Senior Researcher
Pipe & Tube Research Lab.
Steel Research Laboratories
1-8 Fuso-cho, Amagasaki City, Hyogo Pref. 660-0891


Kunio KONDO
General Manager, Head of Lab.
Pipe & Tube Research Lab.
Steel Research Laboratories


Hiroyuki NAGAYAMA
Welding Joint Marketing & Development Dept.
Joint Marketing & Development Div.
Wakayama Works


Hiroyuki HIRATA
Chief Researcher, Ph. D
Welding & Joining Research Lab.
Steel Research Laboratories


Jun NAKAMURA
Researcher
Hydrogen & Energy Materials Research Lab.
Materials Reliability Research Lab.
Steel Research Laboratories


Nobuyuki HISAMUNE
Senior Manager, Head of Dept.
Line Pipe Technology Dept.
Quality Control & Technical Service Div.
Wakayama Works


Masahiko HAMADA
General Manager, Head of Dept.
Welding Joint Marketing & Development Dept.
Joint Marketing & Development Div.
Wakayama Works


Tsuneo MURASE
Senior Manager
Quality Control & Technical Service Div.
Wakayama Works