Advanced Technologies of High Strength Linepipe for Sour Service

by

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Synopsis

Advanced technologies for manufacturing sour service linepipe are introduced. Ultra-clean steel production technology, minimizing type B non-metallic as well as type A inclusions, have been investigated in steel making. Accelerated controlled cooling has been applied to provide both sour resistance and low temperature toughness in low C steel with good weldability in plate rolling. A new alloy concept of Cr addition has been investigated for X 80 sour service linepipe. A high power LASER welding process has been introduced for researching new possibilities. Full ring testing has been applied to evaluate the sour resistance of actual pipes manufactured by the above technologies in addition to small coupon testing.

1. Introduction

HIC (Hydrogen Induced Cracking) and SSC (Sulfide Stress Cracking) are the most serious corrosion problems for linepipes. The first failure occurred on a subsea pipeline in the Persian Gulf in 1972. Since the failure, the mechanism and countermeasures have been investigated, and linepipe steels resistant to HIC and SSC have been developed [1]. Resistance has been improved with the development of critical wells containing higher H_2S and CO_2. In addition, low temperature toughness and weldability are required for offshore pipelines and in cold districts. A high strength grade of API 5LX 80 has recently been tailored for higher pressure operation. **Figure 1** summarizes these quality requirement changes for linepipe steels[2]. Production technologies have been improved in order to satisfy them. Advanced technologies for steel making, plate rolling, pipe making and testing are introduced in this paper, reviewing the history of developing sour service linepipes.

2. Mechanisms of HIC and SSC

HIC and SSC are types of hydrogen embrittlement occurring in ferritic steels. Hydrogen enters steel with the corrosion in wet H_2S environments (sour environments)[3]. The hydrogen is trapped around nonmetallic inclusions in steels[4]. The hydrogen gas pressure is a driving force of HIC. The hydrogen is also trapped in low temperature transformation microstructures which are often formed at the center segregated portion of Mn and P[5]. The low temperature transformation microstructures have high susceptibility to HIC because they are generally very hard, due to martensitic transformation. Two initiation sites of HIC are shown in **Fig. 2.**

Two types of SSC are observed in linepipe steel[1]. One is HIC inducing SSC, which is often called SOHIC (Stress Oriented HIC). This type of SSC occurs in base metal or softened HAZ (Heat Affected Zone) as shown in **Table 1.** Although the microstructure affects the susceptibility[5], care should also be taken with inclusions because the crack occur-

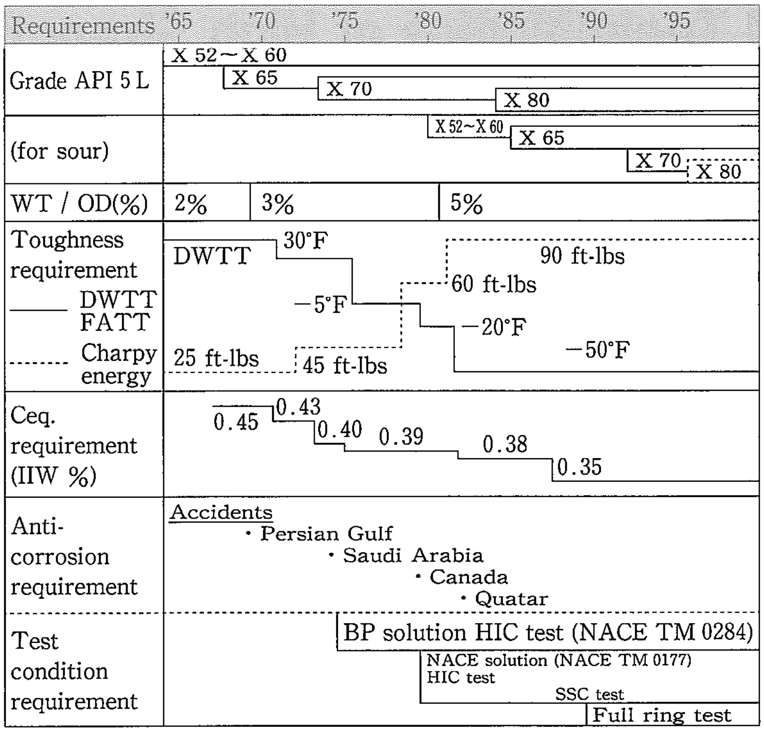


Fig. 1 General guality reguirement for high strength linepipe

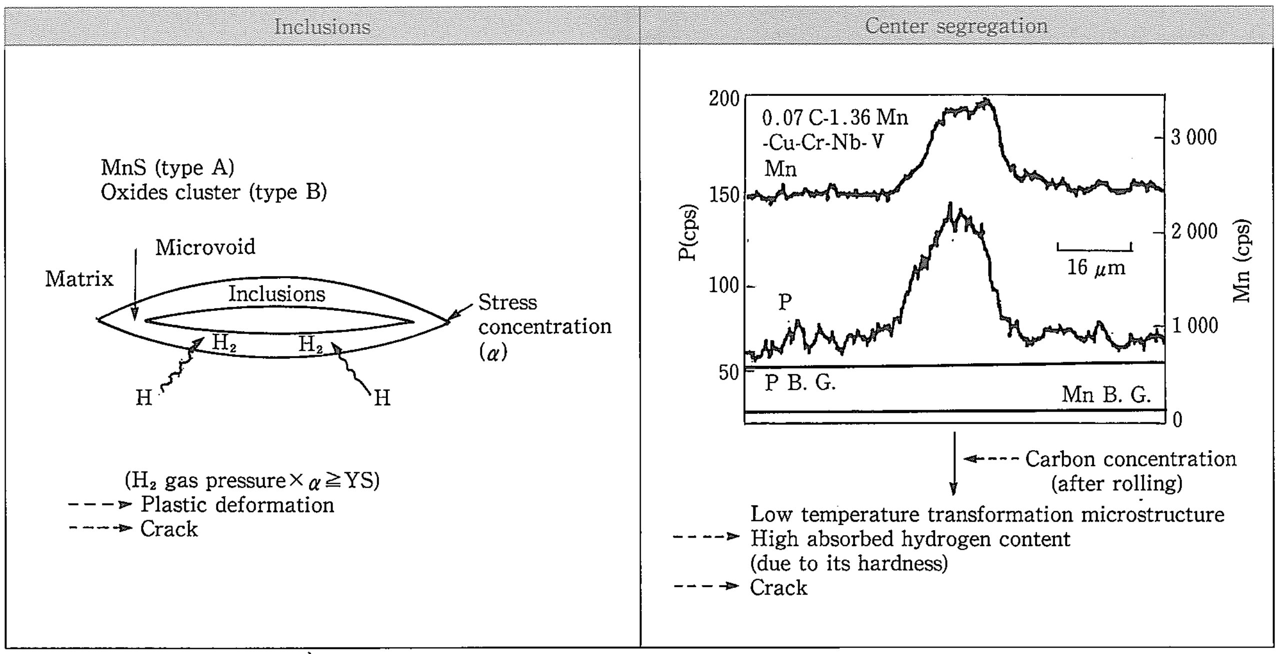


Fig. 2 Initiation sites of HIC in linepipe steel

rence around inclusions is accelerated by stress. The other is hydrogen cracking at hard portions such as HAZ near fusion lines or weld metal overmatched with (harder than) base metal.

Although it is important to eliminate these initiation sites to develop sour resistant steels, reasonable criteria should be considered because hydrogen embrittlement always occurs when absorbed hydrogen content (C_0) in steel exceeds the threshold hydrogen content (Cth) of the steel[6]. In other words, there is no steel which is not damaged when the testing conditions become more and more severe.

Table 1 SSC at weldment in linepipe steels

Type	Type II	Type I (HIC induced)	
Factor	Hardness	Softening	Microstructures
SSC	SSC W.M. | HAZ | B.M.	SSC W.M. | HAZ | B.M.	SSC W.M. | HAZ | B.M.
Characteristics	Near fusion line Coarse grain Hardest portion	Above Ac 3 Fine grain Softest portion	Above Ac 1 Dual phase

3. Steel Making

HIC and SSC occurs around non-metallic inclusions as described above. Eliminating these inclusions is a principal rule for steel making of sour service steels. Type A inclusions like MnS, elongated by plate rolling, are the most harmful because they have high stress concentration with piled up hydrogen gas pressure[4]. Therefore, The first applied technology was the desulfurization and the shape control of sulfides by Ca treatment(addition) as shown in **Fig.3**[7]. This clean steel production technology has been widely used.

It is found that type B inclusions, which are disconnected oxides containing Ca, Al and S, become initiation sites in severe testing conditions under stress[8]. Therefore, it is necessary to minimize these oxide inclusions. Moreover, it is important to obtain the suitable composition of CaO, CaS and Al_2O_3 in inclusions in order to prevent the formation of type B inclusions in plate rolling. A kinetic model has been developed for calculating the inclusion composition during Ca treatment[9]. It has become easy to control the composition by using this model as shown in **Fig. 4.** This ultra clean steel production technology, in addition to the conventional control of Ca/S ratio, is necessary for linepipe steel with higher strength, such as X 80, because the higher strength steel has higher susceptibility to HIC and SSC.

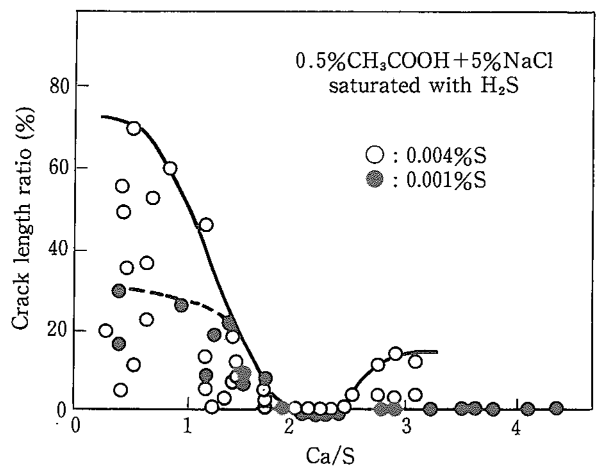


Fig. 3 Effect of Ca/S ratio on HIC susceptibility in low S, Ca-treated steel

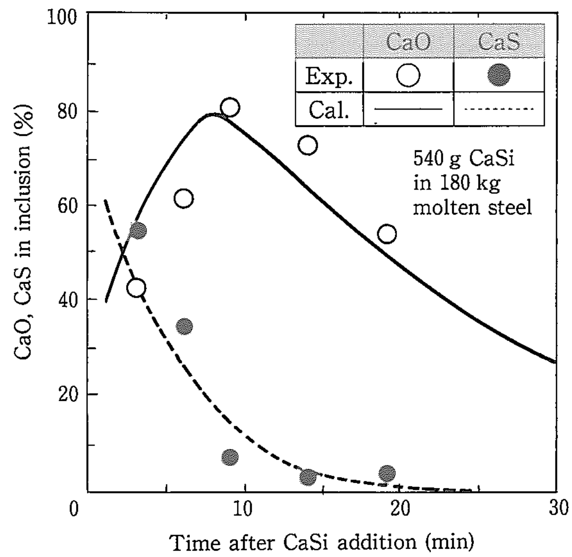


Fig. 4 Comparison between calculation and experimental results of inclusion composition

4. Alloy Design and Microstructure Control

Alloy design and microstructure control are important for producing plates with good combination of strength, toughness and weldability while preventing the formation of low temperature transformation microstructures at center segregated portions. Decreasing C, Mn and P content is effective in reducing the segregation. Decreasing C is also effective in improving toughness and weldability. The required strength can be obtained in these low C steels by TMCP (Thermo Mechanical Controlled Process) and addition of microalloying elements [10]. Typical chemical composition of X 65 steel are 0.05 C-1.3 Mn-<0.01 P-<0.001 S-Nb-V-Ti-Ca. Moreover, Cu and Ni can be optionally added for strengthening while retaining good toughness and sour resistance.

The key technology in the TMCP is the accelerated controlled cooling above temperature Ar_3 giving uniform and fine microstructures as shown in **Fig. 5.** High temperature finish rolling for this DAC (Dynamic Accelerated Cooling) process is also useful in preventing elongation of inclusions. These concepts are common to the rolling and coiling process of hot strip for ERW linepipe. Cooling equipment after rolling is being improved year by year.

The above alloy design can be applied to up to API 5 LX 70 grade sour resistant steels. Cr addition has been investigated for X 80 steel, because a small amount of Cr (less than 1 % or so) has no relation with center segregation and can give good hardenability in the DAC process. The addition of 0.5 % Cr can strengthen plate up to X 80 without deterioration of HIC resistance as shown in **Fig. 6.** X 80 linepipe for sour service will be discussed in a few years.

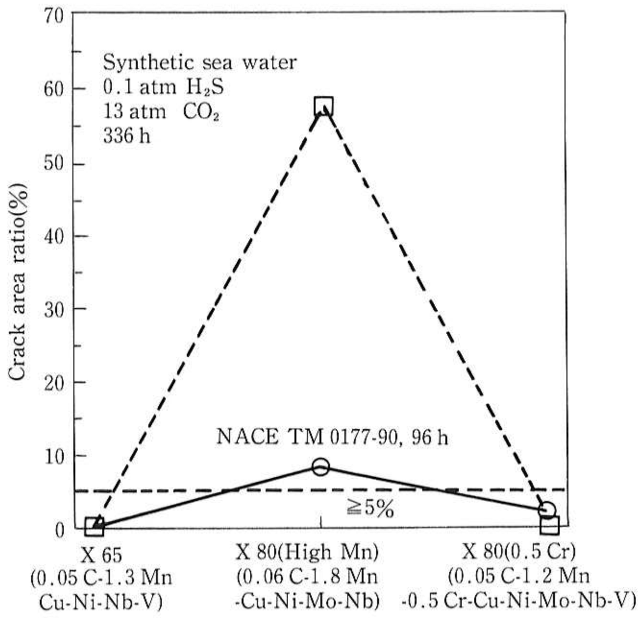


Fig. 6 Research of Cr addition for X80 sour grade linepipe

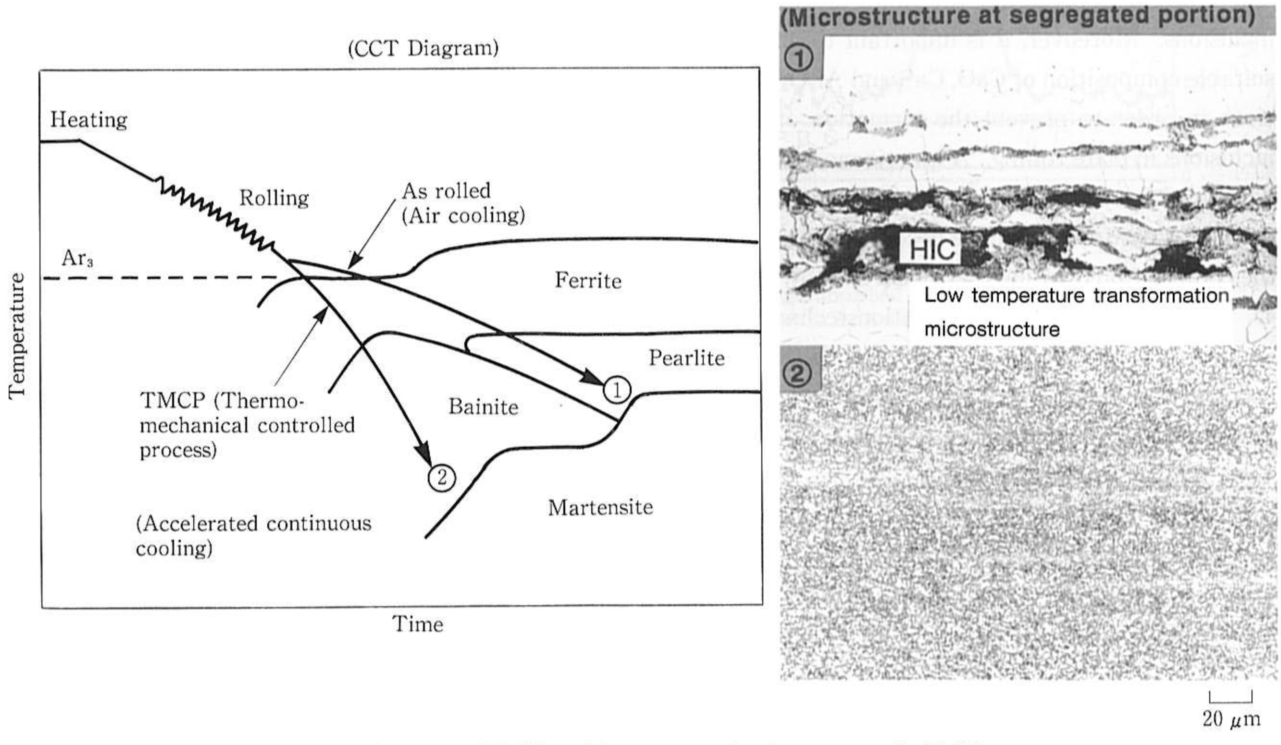


Fig. 5 Concept of TMCP and improvement in microstructure by TMCP

5. Seam Welding

Two welding processes, SAW (Submerged Arc Welding) and ERW (Electric Resistance Welding), are used for manufacturing welded linepipes in SMI. The key technologies for the SAW process are as follows. Hardness control in the weld metal and HAZ near the fusion line are important technologies from the view point of SSC prevention, because the UOE pipe making process does not generally include PWHT (Post Weld Heat Treatment) after SAW. **Figure 7** shows the effect of hardness at the weldment on SSC resistance. The hardness limitation in NACE TM 0177-90 method A (standard tensile testing method) is around 230 Hv. The hardness of weld metal should be controlled without undermatching, especially in X 80 grade linepipe. Another technology is the reduction of residual stress after pipe forming by expansion.

The ERW process is applied to manufacture of medium diameter pipe with thin wall thickness. **Figure 8** shows the production range in each pipe making process in SMI. The heat input and upset are controlled under inert gas shielding in order to prevent welding defects in the ERW process. Induction PWHT is usually applied to improve the performance of the ERW weld seam. Although the ERW linepipe has good HIC and SSC resistance as described later, a high power (25 kW) LASER welding process with high frequency induction preheating has been introduced for researching new possibilities. **Figure 9** shows the manufacturing process. No harmful defects occur in the LASER welding process due to fusion welding. In addition, in-line PWHT is effective in improving the HAZ microstructure and reducing the microhardness distribution. This LASER welding process with PWHT has the advantages of both SAW and ERW processes as shown in **Table 2**[11] and promises to be a fruitful technology.

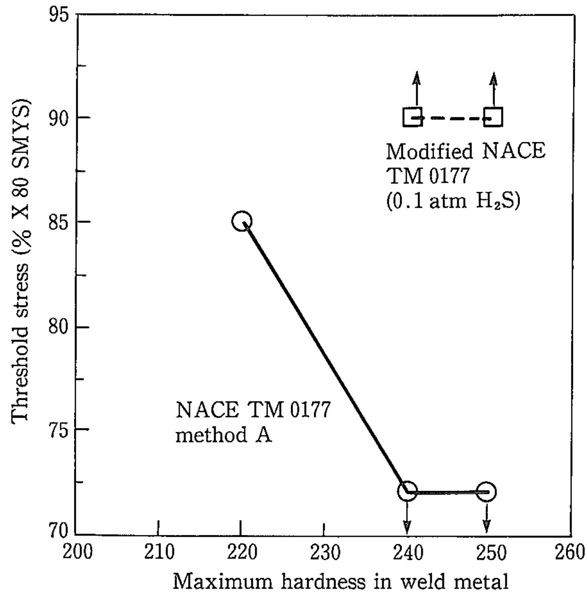


Fig. 7 Effect of hardness on threshold stress at weldment

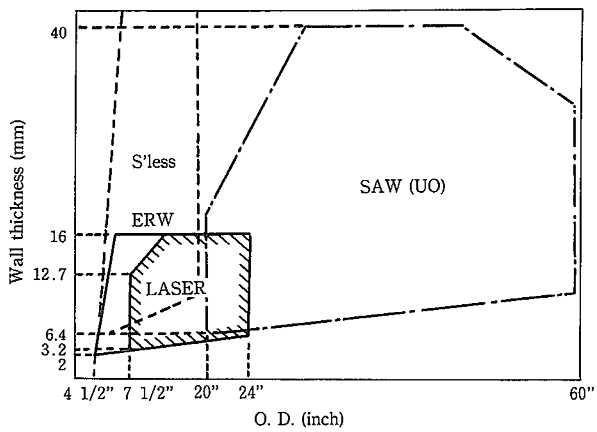


Fig. 8 Available size range of each mill in SMI

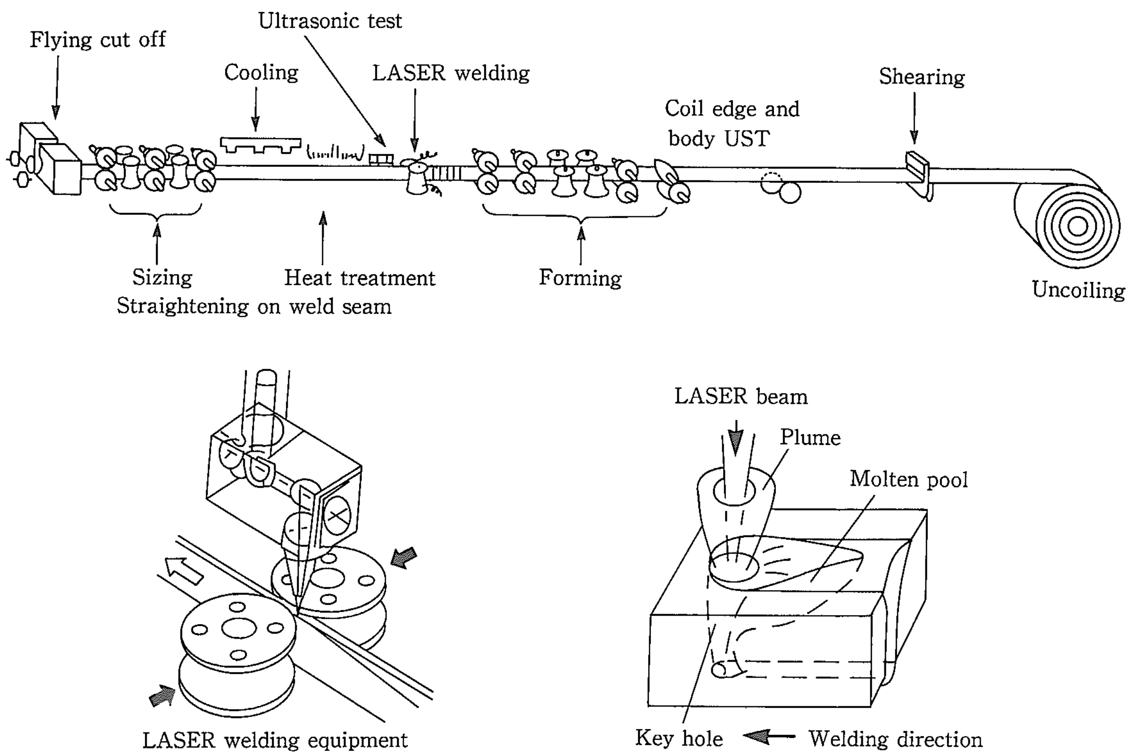
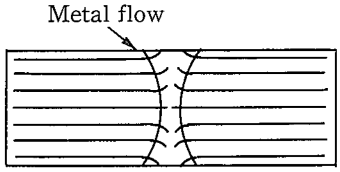
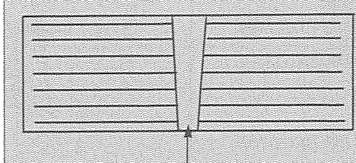
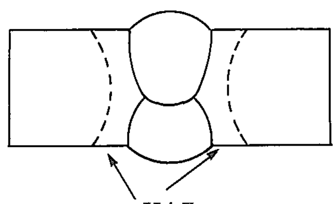


Fig. 9 Manufacturing process of LASER welded pipe

Table 2 Advantages of high power LASER welding with PWHT compared with conventional ERW and SAW

ERW	High power LASER (without filler)	SAW
Metal flow 	 weld metal	 HAZ
Limitation of oxidizable elements (Cr, Si, Mn)	No restriction of chemical composition for welding	
	Rapid solidification → No segregation → No de-alloying element	
Pressure welding	Fusion welding → No defects	
Upset → metal flow	Slight upset → Slight metal flow	
Induction PWHT on weld seam → Improvement in microstructure & microhardness		As-weld → HAZ

6. Testing Method

The history of developing steels is that of developing testing methods. Small coupon tests[3], which have been finally standardized in NACE TM 0284 or NACE TM 0177, have contributed to the development of sour resistant steels. They are widely used as the specification tests of products because they are relatively convenient. Recently, the full ring test using actual pipes has been investigated[12]. These testing methods are summarized in **Table 3.** This full ring test has advantages as follows.

1) evaluated under applied stress with residual stress
2) evaluated under hydrogen concentration gradient in pipe wall
3) evaluated in much larger area with actual surface condition
4) evaluated quantitatively by measuring hydrogen permeation

The reliability of sour service linepipe has been estimated by this full ring test. For example, as shown in **Fig. 10**, it can be predicted that no HIC occurs in SAW linepipes under actual conditions because the threshold hydrogen permeation is much lower than the environmental permeation, and it has been proved that the ERW seam has excellent sour resistance[13]. The reliability of X 80 sour service linepipe will be estimated by the full ring test.

7. Conclusions

Recent advanced technologies for manufacturing sour service linepipes are introduced. They are all technologies in iron & steel industries, such as steel making, plate rolling, pipe making and testing. They are constructed on work which has been continuously researched since HIC and SSC phenomena were found. They will be further improved to satisfy future technological and economical requirements.

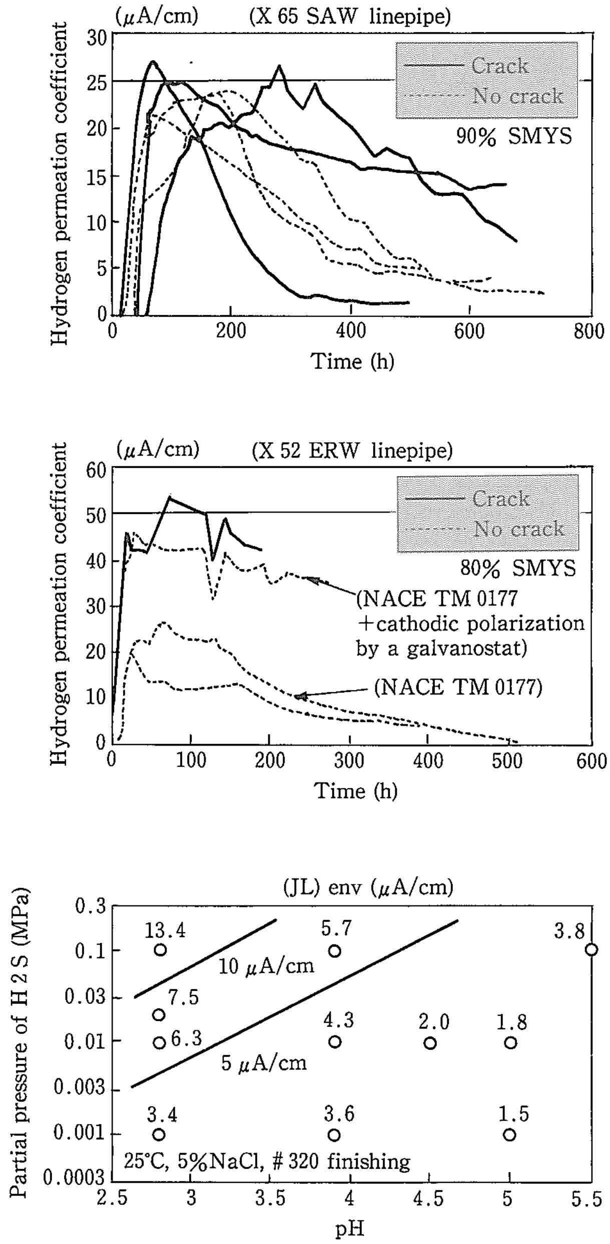
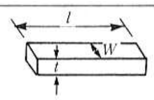
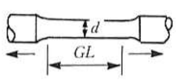
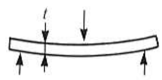
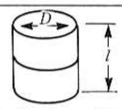


Fig. 10 Threshold hydrogen permeation of typical sour service linepipes and environmental hydrogen permeation in some sour environments

Table 3 Test method of linepipe steel for sour service

	Small scale laboratory test			Full ring test
Item	NACE TM 02 84	NACE TM 01 77 method A		
Test specimen	 20×100×(WT-2)	 d=6.4 ϕ, GL=25.4	 t=5, w=15, l=115	 Full ring $l \geq$D
Solution	NACE TM 02 84 pH 5.0 NACE TM 01 77 pH 3.0	NACE TM 01 77 pH 3.0	NACE TM 01 77 pH 3.0	NACE TM 01 77 pH 3.0
H_2S pressure	0.1 MPa (1 atm)	0.1 MPa	0.1 MPa	0.1 MPa or simulated pressure
Hydrogen entry	All surfaces	All surfaces	All surfaces	Pipe inner surface
Test temp.	25±3°C	24±3°C	25±3°C	25±3°C
Stress	None	Tensile stress	Bending stress	Bending stress
Test duration	96 hrs.	up to 720 hrs.	30 days	30 days

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