JFE TECHNICAL REPORT
No. 2 (Mar. 2004)

Steels for Production, Transportation, and Storage of Energy†

DESHIMARU Shinichi[*1] TAKAHASHI Kazuhide[*2] ENDO Shigeru[*3] HASUNUMA Junichi[*4] SAKATA Kei[*5] NAGAHAMA Yutaka[*6]

Abstract:

JFE Steel produces a wide variety of steel plates and tubular products for energy development, transportation and storage. This paper introduces high strength steel plates for pressure vessels and high toughness plates for offshore structures, and describes the continuous casting and forging technologies for high performance steels. JFE Steel also produces a full range of tubular products for the energy industry, including UOE pipes, ERW pipes and seamless pipes. Among them, this report describes high performance products such as oil country tubular goods and corrosion resistant pipes with special emphasis on linepipes.

1. Introduction

Steel products are used in great quantity in the production, transportation and storage of energy resources such as oil and natural gas. Examples include oil country tubular goods (OCTG) for extraction of natural gas from the earth, steels for offshore structures used in drilling rigs in the sea, linepipes for transportation from gas fields to consuming regions, materials for oil tankers and LNG ships, and steels for pressure vessels for gas storage. As a result, steel products are assuming ever greater importance in the energy industry.

Considering pipeline materials as an example, performance requirements have risen steadily over the years. As shown in **Fig. 1**, API X52 class steel was used before 1965, and the practical application of X100 began in 2002. This means that strength requirements have doubled in the past 35 years. High strength steels are also increasingly used as materials for pressure vessels. In addition to high strength products, JFE Steel has also developed pipes such as HIPER, which have excellent resistance to buckling caused by ground movement due to earthquakes.

In response to increasing energy demand, deep wells and those with unprecedented severe corrosion environ-

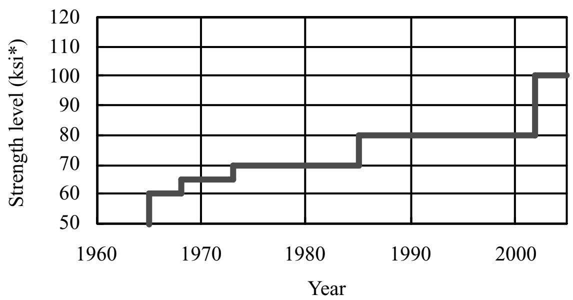

Fig. 1 History of high strength linepipe

† Originally published in *JFE GIHO* No. 2 (Nov. 2003), p. 51–62


*1 Manager,
Plate & Forging Sec., Products Design & Quality Control for Steel Products Dept.,
West Japan Works,
JFE Steel


*2 Dr. Eng.,
Senior Researcher Deputy General Manager,
Plate & Shapes Res. Dept.,
Steel Res. Lab.,
JFE Steel


*3 Dr. Eng.,
Senior Researcher Manager,
Plate & Shapes Res. Dept.,
Steel Res. Lab.,
JFE Steel


*4 General Manager,
Products Service & Development Dept.,
Chita Works,
JFE Steel


*5 Dr. Eng.,
General Manager,
Tubular Products & Casting Res. Dept.,
Steel Res. Lab.,
JFE Steel


*6 General Manager,
Tubular Products Business Planning Dept.,
JFE Steel

ments are now being developed. The CO_2 corrosion is a problem in wells with high CO_2 concentration, while hydrogen induced cracking (HIC) and sulfide stress corrosion cracking (SSCC/SSC) are the problems in wells with high H_2S. For these environments, JFE Steel developed high performance corrosion resistant materials such as 13% Cr OCTG, weldable 12% Cr linepipes, and linepipes for sour service. JFE Steel has also developed structural materials and linepipe materials with excellent low temperature toughness for the wells in arctic climates as observed in Sakhalin, Alaska and the North Sea.

A diverse range of material property requirements are placed on steel products in the energy production sector. In addition, high quality is also required to secure reliability and safety when handling high pressure gas. To satisfy these requirements, JFE Steel mainly uses TMCP steel in plate and UOE pipe products. In particular, the plates with both high strength and excellent weldability and toughness are manufactured by applying JFE Steel's state-of-the-art *Super*-OLAC (on-line accelerated cooling) device. This paper introduces JFE Steel's representative products for the energy industry.

2. Steel Plates

2.1 High Performance 610 N/mm² Class High Strength Steel for Pressure Vessels

Various types of plate are used in the energy sector, for example, in energy storage facilities, chemical plants and power plants. In recent years, the scale of these facilities has increased and the operating and service conditions have become more severe, while at the same time, higher efficiency has been demanded in welding and other work to reduce construction cost. In response to these trends, increasingly high performance requirements are now placed on materials, ranging from high strength to improved weldability and improved reliability, including welds, where high weld toughness is required. To meet these needs, JFE Steel developed a series of high performance the 610 N/mm² class high strength steel plate[1)] as shown in **Table 1** by making full use of its advanced material design and manufacturing technologies. The chemical composition of these plates is shown in **Table 2**. The JFE-HITEN610U2 has excellent weldability and weld toughness. In addition to these properties, the 610E has superior high heat input weldability, and the 610U2L provides excellent low temperature toughness. They conform to "Steel plates for pressure vessels SPV490" of JIS G3115. As features, lower preheat temperature can be used (**Fig. 2**) and weld hardness is reduced by adopting a low C and low carbon equivalent (P_{CM}) value design in comparison to the conventional steels.

Figure 3 shows the results of a maximum hardness test of JFE-HITEN610U2. A low HAZ hardness of Vick-

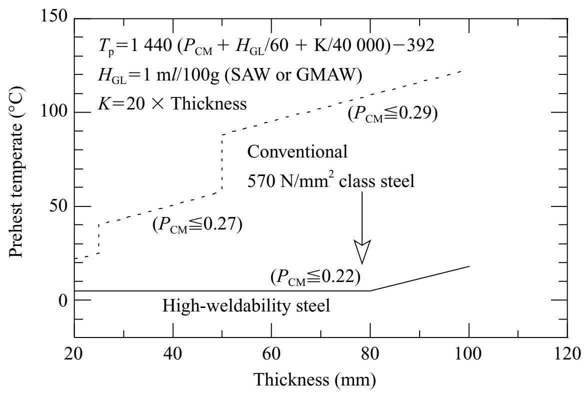

Fig.2 Example of the decrease in required pre-heat temperature for low P_{CM} HSLA steel plates[2)]

Table 1 JFE Steel's 610 N/mm² class high performance steel plates for pressure vessel

Grade	Available thickness (mm)	Feature	JIS	WES certification			Applications
				WES3001	WES3009	WES3003	
JFE-HITEN 610U2	6 ≦ t ≦ 75	Excellent weldability, superior toughness, etc.	JIS G3115 SPV490	HW490 QB	HW490Q CF	–	Penstock, tank, pressure vessel, etc.
JFE-HITEN 610E	6 ≦ t ≦ 75	Excellent weldability, superior properties of weldments for high-heat input welding, superior toughness, etc.				–	Oil storage tank, etc.
JFE-HITEN 610U2L	6 ≦ t ≦ 75	Excellent weldability, superior toughness at lower temperature, etc.				LT490-75 −50G Q	Tank for low temperature use, etc.

Table 2 Chemical compositions of JFE Steel's 610 N/mm² class high performance steel plates for pressure vessel

(mass%)

Grade	C	Si	Mn	P	S	Others	C_{eq}	P_{CM}
JFE-HITEN610U2 JFE-HITEN610E	0.09 max.	0.15–0.55	1.00–1.60	0.020 max.	0.010 max.	Cu, Ni, Cr, Mo : 0.30 max., V : 0.06 max., Nb : 0.03 max.	0.44 max.	0.20 max.
JFE-HITEN610U2L	0.09 max.	0.15–0.55	1.00–1.60	0.015 max.	0.005 max.			
cf. JIS G 3115 SPV490	0.18 max.	0.15–0.75	1.60 max.	0.030 max.	0.030 max.	Alloying elements other than those listed may be added.	0.45 max.	0.28 max.

C_{eq}= C+Si/24+Mn/6+Ni/40+Cr/5+Mo/4+V/14
P_{CM} = C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+Mo/15+V/10+5B

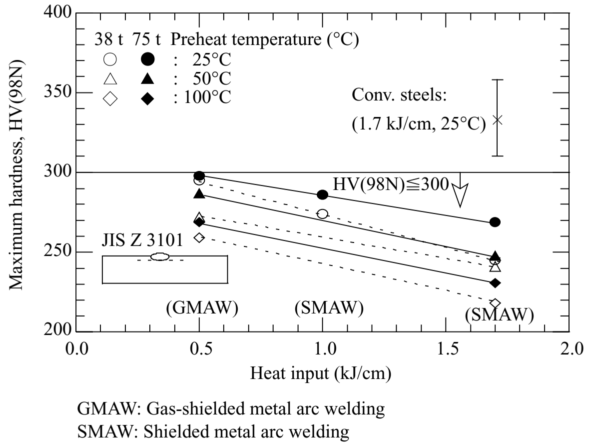

Fig. 3 Maximum hardness of JFE-HITEN610U2

ers hardness HV(98N) ≦ 300 points or less is obtained under all welding conditions, realizing a large reduction in weld hardness in comparison to the conventional steel.

As the material for side plates of large oil storage tanks and similar applications employing high efficiency and high heat input electro gas arc welding, a 610 N/mm^2 class high strength plate JFE-HITEN610E for high heat input welding has already been adopted in a large number of projects, taking advantage of its improved joint strength and weld toughness under these welding conditions.

JFE Steel also developed a high toughness, 610 N/mm^2 class high strength steel plate for low temperature use, JFE-HITEN610U2 with properties including low temperature toughness to −50°C, which has a record of use of low temperature tanks.

All of these new steels were developed by applying a fusion of advanced plate manufacturing technologies and microalloying techniques to meet diverse needs.

As shown in Table 1, these products have been certified as steel grades under the Japan Welding Engineering Society (JWES) standards specified in WES 3001-1996 (Weldable High Strength Steel Plate), WES 3009-1998 (Supplementary Requirements for High Strength Steel Plate with Low Susceptibility to Cold Cracking) and WES 3003-1995 (Evaluation Criterion of Rolled Steels for Low Temperature Application). These products have a record of use in various types of tanks and penstocks in numerous projects, particularly in China and other Asian countries which have achieved remarkable economic development in recent years and are actively constructing large-scale energy plants. The JFE-HITEN610U2, 610U2L and other products have received general certification in material ratings by the China Standardization Committee on Boilers and Pressure Vessels.

2.2 High Toughness Steel for Offshore Structures

With active development of petroleum energy resources in recent years, the locations of offshore structures have extended to icy and deep waters, while high strength and heavy gauge products have been adopted in steel plates as such. In icy waters, the temperature at which fracture toughness CTOD (crack tip opening displacement) is required has been reduced from the conventional −10°C to −40°C.

For JFE Steel's offshore structures, rapid cooling by the *Super*-OLAC makes it possible to manufacture heavy section plates with a maximum thickness of 101.6 mm for a YP420 MPa class steel. [3)]

JFE Steel recently developed a plate with the thickness of 75 mm which can guarantee a CTOD value of 0.38 mm at −40°C for the welded joint.[4)] The chemical composition of this plate is shown in **Table 3**. In addition to the conventional HAZ toughness countermeasures of low C, low N, low Si, low P and Ti treatment, 1.1% Ni is added to secure toughness, particularly at low temperatures. **Figure 4** shows the CTOD values of the welded joints made by submerged arc welding (SAW) with a heat input of 5.0 kJ/mm. Extremely stable properties are obtained.

Higher strength YP460 MPa and YP500 MPa class steels are also being used. JFE Steel has developed a succession of commercial products of these grades which meet the requirements of various projects.

2.3 Forging-Rolling Process for Continuous Cast Slabs

As a manufacturing process for high quality, ultra-heavy section plates produced from continuous cast (CC) slabs, JFE Steel developed a process technology which applies forging to CC slabs before plate rolling.[5,6)] The effects of this forging-rolling process include improved internal quality and mechanical properties in the central parts of plate thickness, which are achieved by closing and crushing center porosities, and improved homo-

Table 3 Chemical composition of steel plate developed

(mass%)

C	Si	Mn	P	S	Cu	Ni	Nb	C_{eq} *1	P_{CM} *2	Note
0.07	0.10	1.55	0.005	0.001	0.29	1.09	0.015	0.42	0.18	Ti treated

*1 C_{eq}=C+Mn/6+(V+Mo+Cr)/5+(Cu+Ni)/15
*2 P_{CM}=C+Si/30+(Mn+Cu+Cr)/20+Ni/60+Mo/15+V/10+5B

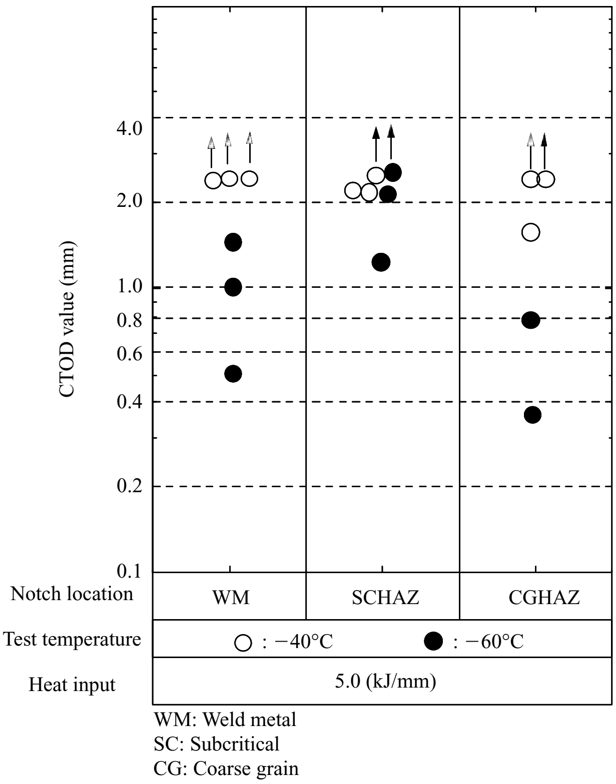

Fig. 4 CTOD values for SAW welded joints of steel plate developed

geneity in the thickness direction by alleviating center segregation. JFE Steel manufactures ultra-heavy section plates with sound internal quality for the thicknesses of up to 240 mm (original slab thickness/product thickness = reduction ratio: 1.29) using CC slabs with a thickness of 310 mm, and has already produced more than 60 000 t for various applications. As this technology has been recognized as an essential process for relaxing restrictions on the reduction ratio (from 3 or higher to 2 or higher) in provisions relating to general conditions for steel plates for pressure vessels in the ASTM Standard 2002 A20/A20M and ASME 2002 Addenda SA-20/Sa-20M, it is expected to play a key role in expanding the applications of ultra-heavy section plates manufactured from CC slabs.

A flow chart of manufacturing process and a schematic diagram of forging operation are shown in **Figs. 5** and **6**, respectively. The actual forging press operation in slab thickness reduction is shown in **Photo 1**. As shown in Fig. 6, by using a bidirectional forging reduction method in which slab thickness reduction is performed after reduction in the slab width direction, and performing forging reduction in the thickness direction with an appropriate B/H_0 (B: forging anvil bite width, H_0: original slab thickness), compressive plastic strain in the width and thickness directions is effectively applied to the slab center of thickness, achieving improved internal quality.

Since the center segregation is alleviated and the

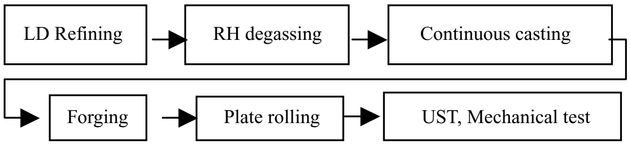

Fig. 5 Manufacturing process

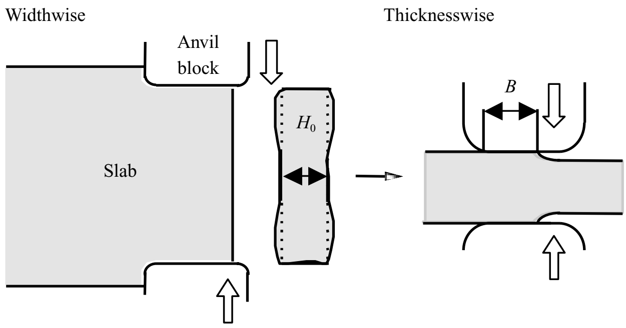

Fig. 6 Schematic diagram of CC slab forging

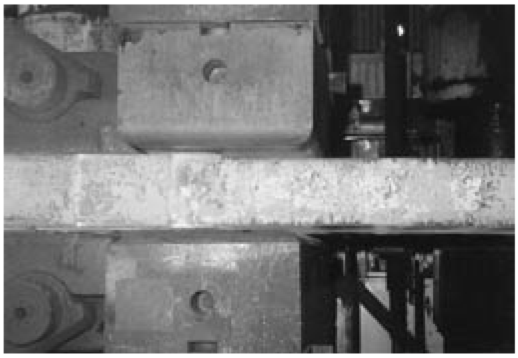

Photo 1 Forging reduction in thickness of CC slab

increased holding time during reheating in the forging process has a desirable diffusion effect, a significant improvement can also be realized in low temperature toughness at the center of plate thickness sensitivity to, temper embrittlement and HIC properties.

Figure 7 shows the influence of the holding time during reheating in forging on the toughness of the 2.25Cr-1Mo steel for high temperature pressure ves-

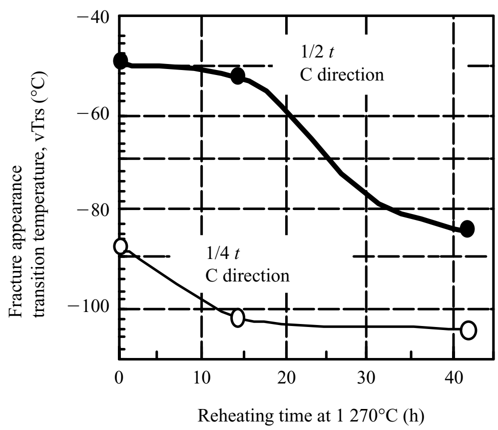

Fig. 7 Influence of reheating time at forging on vTrs

Table 4 Chemical composition of 2.25Cr-1Mo steel

(mass%)

C	Si	Mn	P	S	Cr	Mo
0.14	0.09	0.55	0.007	0.001	2.43	1.05

sels (JIS G4109 SCMV4-2, thickness: 110 mm) with the chemical composition as shown in **Table 4**. In this comparison, only the holding time was varied (reheating temperature: 1 270°C), and the following steps of plate rolling, refining heat treatment, and test piece with simulated post weld heat treatment (PWHT) were performed in the same manner. The property values at reheating time: 0 are for the conventional process without forging. A remarkable increase in toughness at the 1/2*t* position can be observed as the reheating time increases.

3. Steel Pipes and Tubes

3.1 High Strength UOE Linepipes

3.1.1 High strength API X80, X100 linepipes

For the linepipes used to constant long-distance pipelines, there has been a continuing trend toward a higher strength, which makes it possible to increase operating pressure while reducing the quantity of steel used. In 2002, JFE Steel began a commercial production of the world's highest strength linepipes by manufacturing the world's first CSA grade 690 (API X100 grade equivalent). Among other products, JFE Steel began manufacturing X80 linepipes for Canada in 1991 and has produced approximately 50 000 t in total to date. This chapter describes the manufacturing technology and features of X100 grade and other high strength linepipes.

3.1.2 Manufacturing technology for high strength linepipes with high toughness

When using high strength linepipes, excellent low temperature toughness is important for safety, while outstanding field weldability is essential for pipelaying efficiency. To satisfy these requirements, controlled rolling and accelerated cooling are applied in manufacturing the steel plates for high strength linepipes. Accelerated cooling is a technology which JFE Steel put in practice for the first time in the world in 1980 at its West Japan Works (Fukuyama District) plate mill, and is used to cool plates on-line after controlled rolling. Accelerated cooling makes it possible to manufacture high strength, high toughness plates using steel with a lower chemical composition. Subsequently, JFE Steel developed a new accelerated cooling device called *Super*-OLAC, which features a high cooling rate and excellent temperature controllability, symmetrical cooling of the top and bottom sides of the plate and uniform surface temperature profile. It was put into operation in 1998 (**Fig. 8**).[7]

3.1.3 Mechanical properties of X100 linepipe and future developments

Table 5 shows an example of the mechanical properties of an X100 linepipe with an outer diameter of 36" and wall thicknesses of 12.7 mm and 15.1 mm, including transverse tensile, Charpy, and DWTT (drop weight tear test) results. The X100 thoroughly satisfies the strength standards, and a high value of more than 200 J was obtained as the absorbed energy in Charpy test. The 85% shear area transition temperature obtained by DWTT test was below −20°C for both thicknesses, indicating that excellent performance can be obtained, even when used in linepipes in arctic climates.

JFE Steel has also completed development of high frequency bent pipes in grades of up to X80,[8] and has set development of bent pipes, consumables for girth welding, and an optimum welding process for X100 linepipe as future goals. The development of these

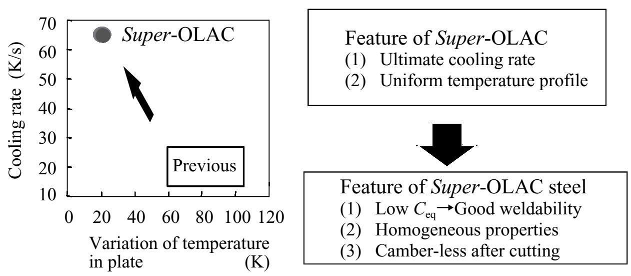

Fig. 8 Main features of *Super*-OLAC system

Table 5 Mechanical properties of API X100 linepipes

Tensile properties (Transverse direction)							Charpy impact properties		DWTT	
Grade	Wall thickness (mm)	Outside diameter (")	Specimen type	YS (MPa)	TS (MPa)	El (%)	Energy at 0°C (J)	50%FATT (°C)	SA at 0°C (%)	85%SATT (°C)
API X100	12.7	36	API (flattened) Round bar	735 850	886 890	23 19	262	−60	100	−28
	15.1	36	API (flattened) Round bar	734 818	923 901	21 16	223	−55	100	−40

YS : Yield strength, TS : Tensile strength, El : Elongation, FATT : Fracture appearance transition temperature,
DWTT : Drop weight tear test, SATT : Shear area transition temperature

peripheral technologies and the study of the above-mentioned ductile fracture behavior are expected to contribute to expanded the application of X80 and X100 linepipes.

3.2 High Deformability UOE Linepipe "HIPER"

3.2.1 Need for development of high deformability linepipe

In addition to high strength and high toughness, the capacity of absorbing large deformation is a necessary property when large strain is expected in pipelines due to earthquakes or other ground movement. The linepipes with diameter/thickness ratios (*D/t*) of around 40 now widely used in Japan have a large deformation capacity, such as a critical buckling strain of 1% or more in a uniaxial compression test. However, as mentioned above, there is a growing tendency to use high strength linepipes such as X80 to reduce the pipe wall thickness, but in this case, buckling strength also generally decreases. Thus, for application of high strength linepipes, it is important to improve the anti-buckling property. Against this background, JFE Steel developed a high deformability linepipe with high buckling resistance. This report describes the mechanical properties and buckling resistance of the developed linepipe.

3.2.2 Features of high deformability linepipe "HIPER"

Generally, critical buckling strain in the uniaxial compression test is proportional to pipe wall thickness and inversely proportional to the pipe diameter. Therefore, if wall thickness is reduced by using a high strength material in a pipeline, the *D/t* increases, reducing critical buckling strain, as shown in **Fig. 9**.

JFE Steel studied buckling strain improvement in high strength linepipe and developed a high deformability linepipe named HIPER, in which high buckling resistance is achieved by increasing the work hardening capacity (*n*-value) of the steel plate. To obtain a high deformation capacity, the accelerated cooling process *Super*-OLAC is applied to manufacturing steel plates. Figure 9 shows the buckling resistance (buckling strain) of HIPER in comparison to the conventional linepipes. The critical buckling strain of HIPER in the uniaxial compression test is more than 1.5 times higher than those of the conventional pipes.

The mechanical properties of HIPER are shown in **Table 6**. It also shows the mechanical properties of welded joints, which are presumed to be used in field welding. HIPER possesses strengths equivalent to those of grades API X65 to X80. Although the conventional linepipes are used at about −10°C and show the absorbed energy of 50 J or higher in the Charpy test and substantially a 100% shear area in the DWTT, HIPER compares favorably with these products, and also shows satisfactory properties in welded joints simulating field girth welding.

3.2.3 Production Record and Future Development of HIPER

The HIPER with a high deformation capacity can be manufactured for the specifications up to API X80 grade. The amount of several thousand tons have already been produced in X65 grade as earthquake-resistant linepipes for the Japanese market. The application of the developed HIPER to gas pipelines makes it possible to construct pipelines with higher safety than with the conventional materials. This benefit is particularly great when using high strength linepipes. With the progressive adoption of high pressure gas pipelines in Japan, an expanded application of HIPER is expected. JFE Steel plans to expand applications to the pipelines running

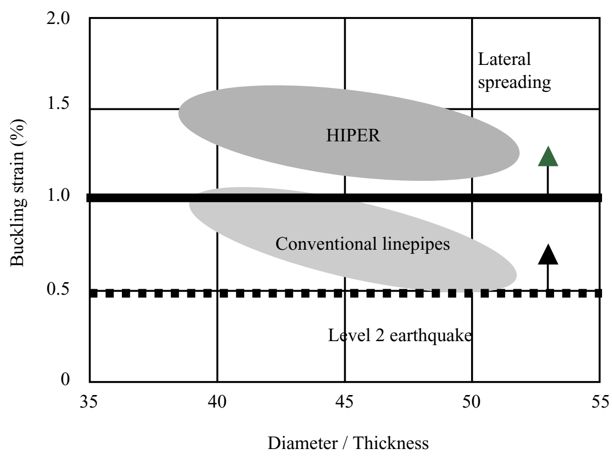

Fig. 9 Critical buckling strain of HIPER

Table 6 Dimensions and mechanical properties of API X65 and X80 HIPER linepipes

API Grade	Dimensions			YS (MPa)	TS (MPa)	Charpy	DWTT	Girth welded joint		
	OD (mm)	WT (mm)	*D/t*			Energy at −10°C (J)	85%SATT (°C)	TS (MPa)	Charpy energy at −10°C (J)	FATT (°C)
X65	711	16	44	468	615	222, 265, 255	−30	670	169, 149, 147	−56
X80	711	18	40	557	751	236, 246, 250	−30	785	124, 178, 142	−57

OD : Outside diameter, WT : Wall thickness, YS : Yield strength, TS : Tensile strength, DWTT : Drop weight tear test,
SATT : Shear area transition temperature, FATT: Fracture appearance transition temperature.

permafrost and sea bottom where large deformation is predicted.

3.3 UOE Linepipes for Sour Service

With the progress in technologies for oil and gas extraction and long-distance transportation, oil and gas reserves are now being developed in the arctic regions and deep sea fields. Accompanying this, there is also a tendency toward diversification in the fluids transported. Consequently, a stable demand for high strength linepipe for sour service is expected in the future.

3.3.1 Manufacturing technology for high strength, high toughness linepipes for sour service

In addition to strength, low temperature toughness and weldability, the properties required for linepipes transporting fluids containing H_2S include sour resistance (resistance to hydrogen induced cracking: HIC, and sulfide stress corrosion cracking: SSCC). Therefore, as new manufacturing technologies, JFE Steel has developed a refining technology for ultra-low S, low P steel, a sulfide morphology control technique using Ca addition and the techniques for reducing macro and semi-micro segregation in the axial center of continuous cast slabs and preventing surface cracks,[9,10] and also has applied controlled rolling and accelerated cooling using the *Super*-OLAC in plate rolling.[11]

3.3.2 Production record and future outlook for high strength linepipes for sour service

Figure 10 shows the trend in the production of linepipes for sour service to date. The main pipe grade is X65. A large volume of production exceeding 100 000 t has been achieved. To meet the rising demand for linepipes suitable for sour service with low H_2S concentration (high pH), which are classified as mild sour in the figure, JFE Steel developed and has supplied linepipes for mild sour service since 1997. Because this type of linepipe reduces pipeline system cost, in the same way as high strength linepipes for sour service, a growing demand is expected in the future.

3.4 High Strength ERW Linepipes with High Toughness

With the progress in material manufacturing and pipemaking technologies, it is now possible to produce high grade, high quality electric resistance welded (ERW) linepipes while also reducing manufacturing cost. As a result, ERW linepipes are increasingly adopted in the fields where UOE or seamless pipes had been used, taking advantage of the superior cost performance of ERW. In particular, with increasing use of high strength linepipes for natural gas, small diameter, thin wall pipes have been adopted, encouraging production of an increasing number of ERW sizes for this application.

JFE Steel is a world leader in this field. The medium diameter ERW pipe mill at JFE Steeel's Chita Works is the only mill capable of manufacturing products with outer diameters up to 26", which is the world's largest ERW pipe size, and has the world's widest available size range, as shown in **Fig. 11**.

In recent years, composite properties have been required in ERW linepipes, including high strength, high toughness with a fracture appearance transition temperature (FATT) of −46°C or under, and resistance to HIC and SSC, considering the use in environments containing hydrogen sulfide. JFE Steel adopted a low C design and optimized the hot rolling conditions to meet these requirements.[11,12] To improve ERW weld toughness, the company established a heat treatment technology and, as shown in **Fig. 12**, has obtained weld toughness with the FATT of −46°C or under by applying the quenching and tempering (QT) treatment to the ERW weld. The quality of ERW weld has greatly improved as a result of this QT treatment. JFE Steel has also succeeded in developing ERW linepipes with high strength, high toughness and high corrosion resistance by developing a pipemak-

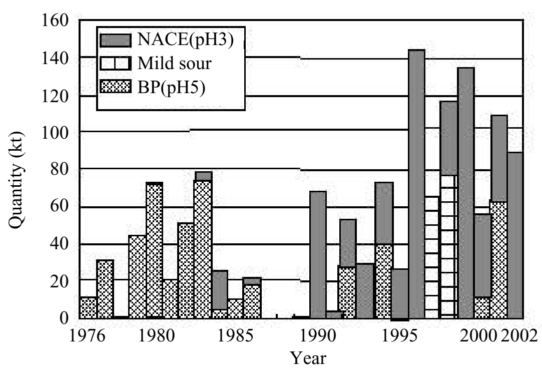

Fig. 10 Production amount of sour gas linepipes

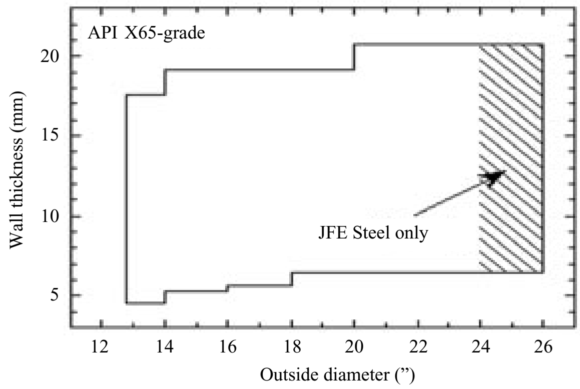

Fig. 11 Available manufacturing size range of X65-grade ERW linepipe of JFE Steel at 26" ERW mill

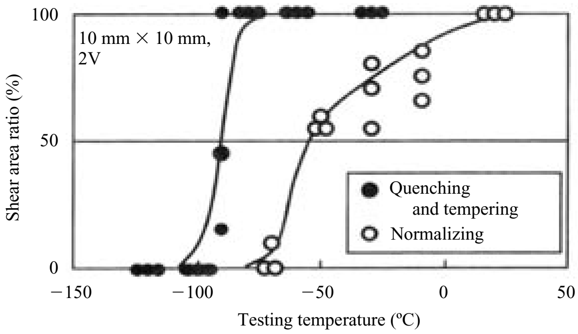

Fig. 12 Charpy impact property of weld seam of X65-grade ERW line pipe

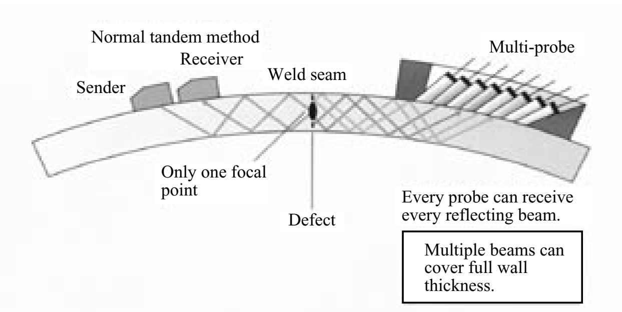

Fig. 13 Schematic image of JFE Steel's new multi-probe system compared with normal tandem method

ing technology which prevents defects in ERW weld.

JFE Steel has continually improved its quality inspection system, which is based on full length, full width inspection of 100% of products. In particular, for weld seam in ERW products, JFE Steel independently developed and introduced the multi-probe system shown in **Fig. 13**, enabling 100% inspection of the pipe wall thickness. Because the reliability of ERW welds has dramatically improved as a result of such an inspection system, application is no longer limited to on land pipelines, but has expanded to offshore pipe lines, including the use in the North Sea. JFE Steel's ERW linepipe displays outstanding quality and has won a high evaluation from major oil companies.

As a result of further study, it is now possible to supply high strength, high toughness and heavy wall ERW linepipes which guarantee CTOD $\geqq$ 0.2 mm at 0°C in both base metal and ERW weld of X65 grade with an outer diameter of 24" and wall thickness of 19.1 mm. JFE Steel is planning to develop ERW products which meet high strength and high toughness requirements for the X80 grade and higher.[13)]

3.5 Heavy Wall ERW Pipes for Conductor Casings

Chita Works expanded the forming equipment at its 26" ERW pipe mill in 2003 and in May of the same year, began commercial production of steel pipes for conductor casings with the maximum wall thickness increased from the former 0.812" (20.6 mm) to 1.000" (25.4 mm). The available range at this mill after the expansion is shown in **Table 7**. Previously, pipes with the wall thickness of 1" could be supplied only as UOE or seamless pipes. As of November 2003, Chita is the only mill which can produce this thickness in ERW pipes. Increasing the wall thickness makes it possible to supply pipes with a maximum collapse pressure approximately 1.6 times greater than that of the conventional ones (**Fig. 14**).

Table 7 Available range at 26" ERW pipe mill

Outside diameter	12.75" (323.9 mm) – 26" (660 mm) (1" wall pipe : 20" (508 mm) – 26" (660 mm))
Wall thickness	0.157" (4.0 mm) – 1.000" (25.4 mm)
Material grade	Up to API 5L X80 (1" wall pipe : API 5L X56)

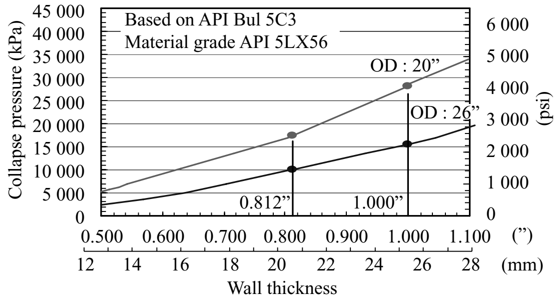

Fig. 14 Calculated maximum collapse pressure for heavy wall pipe

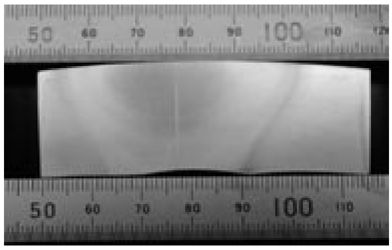

Photo 2 ERW weld seam of 1.000" thick pipe (Nital etched)

Photo 2 shows a macro photograph of the cross section of the ERW weld seam. The weld has good bond and heat treatment zone. For the quality assurance, JFE Steel introduced a multi-probe system described above, enabling 100% flaw detection with ultra-heavy, 1" thick material.

3.6 13Cr Seamless OCTG

The development of petroleum and natural gas is progressing in the direction of deeper wells, and has expanded from land to the sea bottom. In terms of the well environment, development is moving in the direction of increasingly severe conditions, which include high temperature and CO_2/H_2S gas environments. In

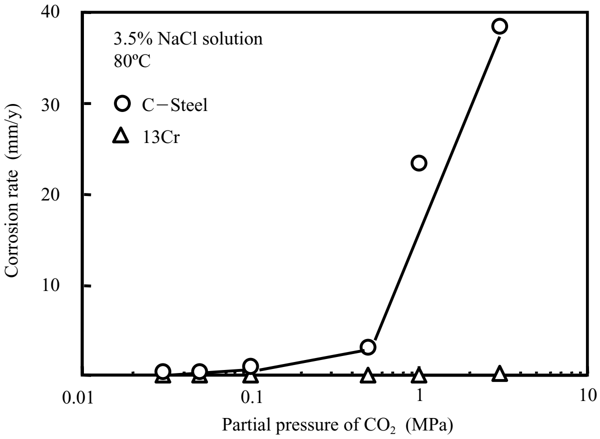

Fig. 15 CO_2 corrosion test result

these highly corrosive environments, the general practice was to coat the inside of the steel tube and use corrosion-preventive chemicals called inhibitors, but for environmental reasons, restrictions have been placed on inhibitors, heightening the need for tubes with high corrosion resistance. Cr addition is effective in improving corrosion resistance in wet CO_2 gas environments.[14] **Figure 15** shows the corrosion rates of carbon steel and 13Cr steel tubes in a CO_2 environment. The 13Cr steel tube shows a greatly reduced corrosion rate in comparison to the carbon steel and can be used without inhibitor, even in the environment with high CO_2 concentration. Since 13Cr showed outstanding corrosion resistance, the need for this product was high from the start of development particularly for the CO_2-containing environments, but no mass production technology existed for this kind of high quality stainless tube. Therefore, as a manufacturing process for seamless 13Cr tubes, JFE Steel developed a comprehensive range of rolling technologies for high alloy steel, including a billet manufacturing technology, piercing technology, mandrel rolling technology and tool life extension technology. Although 13Cr steel tubes had mainly been manufactured by the hot extrusion process up to the time, these new technologies made it possible to manufacture 13Cr tubes with both high dimensional accuracy and high productivity by the Mannesmann process.[15,16] As a result, the market for 13Cr tubes has greatly expanded, to a scale exceeding 100 000 t/y, and JFE Steel now has the world's largest share in the market for 13Cr OCTG.

The 13Cr steel tubes have been standardized in the API standard as L80-13Cr and are used in environments which contain CO_2. However, in high temperature environments exceeding 150°C, CO_2 corrosion resistance deteriorates and they cannot withstand long-term use, and in environments which contain H_2S, sulfide stress corrosion cracking (SSC) is a problem. JFE Steel therefore developed a series of martensitic type stainless steel tubes, HP13Cr, with a new chemical composition which improves CO_2 corrosion resistance and SSC resistance.[17,18] The main chemical compositions of 13Cr and HP13Cr are shown in **Table 8**. To meet the requirements of severe environments at higher temperatures, the content of Cr in solid solution, which is effective in improving corrosion resistance, was increased by reducing the C content, and Ni and Mo were added to secure both hot workability and corrosion resistance. **Figure 16** shows the corrosion rate and applicable service conditions for 13Cr and HP13Cr steel tubes in high temperature, high CO_2 environments. In a 1 MPa CO_2 environment, it is possible to apply 13Cr in the temperature region up to 120°C and HP13Cr up to 175°C.

Table 8 Chemical composition of 13Cr and HP13Cr

(mass%)

	C	Si	Mn	Cr	Ni	Mo
13Cr	0.20	0.20	0.40	13	0.1	–
HP13Cr-1	0.025	0.25	0.45	13	4.0	1.0
HP13Cr-2	0.025	0.25	0.45	13	5.0	2.0

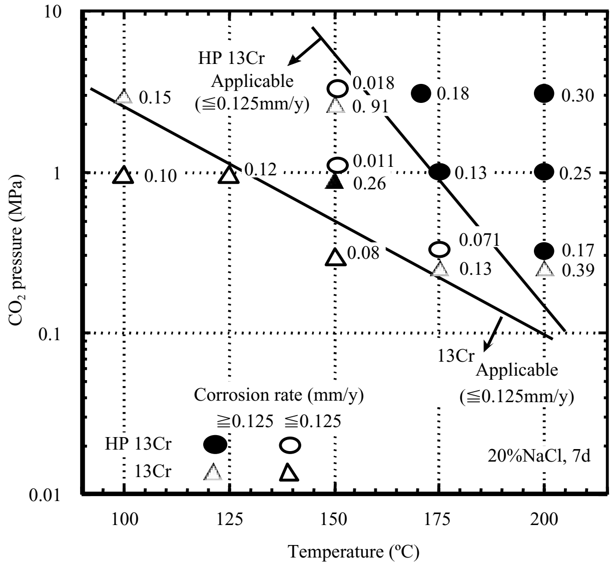

Fig. 16 CO_2 corrosion map for 13Cr and HP13Cr

In particular, Mo addition improves the pitting corrosion resistance of HP13Cr, which gives an initiation site for SSC. This makes it possible to apply HP13Cr in more severe H_2S environments than 13Cr. **Figure 17** shows an example of SSC test result for HP13Cr-1 (1% Mo) and 2 (2% Mo). Owing to its higher Mo content, HP13Cr-2 can be used in lower pH and higher H_2S environments.

Because 13Cr OCTG can be used without inhibitors even in severe environments which contain CO_2/H_2S, steady growth of demand is expected particularly for natural gas development.

3.7 Weldable 12Cr Seamless Linepipes

In the pipelines called flow lines and gathering lines,

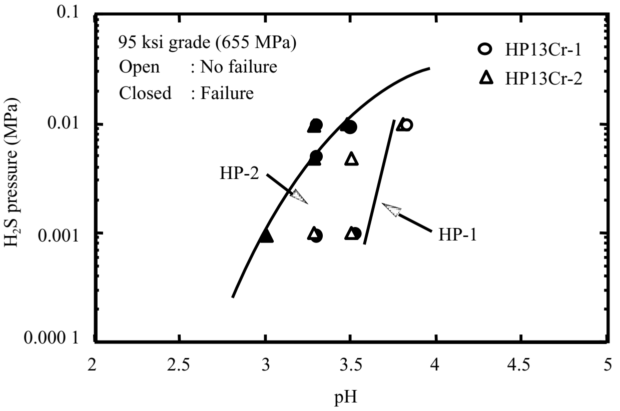

Fig. 17 SSC test result for HP13Cr pipe

which are used to transport the products before being refined in strongly corrosive oil and gas fields containing CO_2/H_2S, measures to prevent CO_2 corrosion and sulfide stress cracking (SSC) are necessary. Though the injection of inhibitor or expensive corrosion resistant materials such as duplex-phase stainless steel were generally used as countermeasures in pipelines, inhibitors increase operating cost, while duplex-phase stainless steel raises material cost. JFE Steel therefore developed a weldable 12Cr seamless linepipe as a new material which reduces the life cycle cost.

The weldable 12Cr seamless linepipe is of a martensitic stainless steel. Since martensitic stainless steels generally have poor weldability, requiring preheating for welding, it had rarely been used in pipeline laying work, where welding efficiency is important. Weldability of JFE Steel's weldable 12Cr stainless steel linepipe is improved by reducing both C and N to 0.01 mass%, enabling welding without preheating. JFE steel also developed two types of weldable 12Cr seamless linepipe, KL-12CR for CO_2 environments and KL-HP12CR for CO_2 + a small amount of H_2S environments, by adding proper amounts of Ni, Mo and other elements which are effective in improving corrosion resistance.[19] The chemical compositions of these two steels are shown in **Table 9**.

Figure 18 shows the results of the CO_2 corrosion test of KL-12CR. The corrosion rate of KL-12CR is approximately half that of the 0.2C-13Cr steel tube for OCTG use, and thus displays excellent CO_2 corrosion resistance. **Figure 19** presents the results of the SSC test of a KL-HP12CR welded joint, showing that it can be used

Table 9 Chemical composition of two types of weldable 12Cr seamless line pipe

(mass%)

Material	C	Cr	Ni	Mo	Cu	N
KL-12CR	0.01	11	2.4	–	0.5	0.01
KL-HP12CR	0.01	12	5.5	2.0	–	0.01

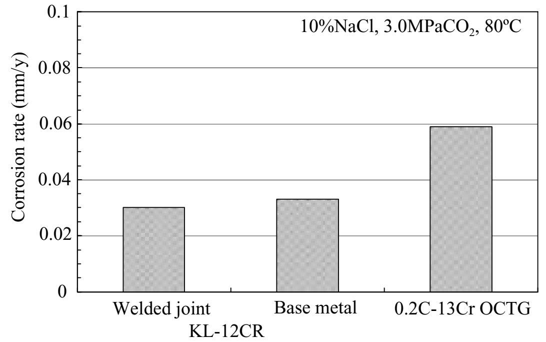

Fig. 18 CO_2 corrosion test results of KL-12CR welded joint

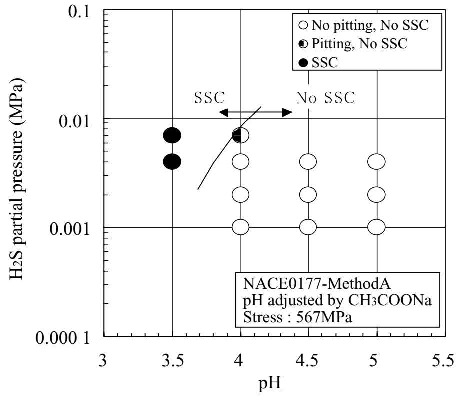

Fig. 19 SSC test results of KL-HP12CR welded joint

in the environments which contain a small amount of H_2S. The strengths of KL-12CR and KL-HP12CR are of X70 and X80 classes, respectively, and toughness is of a level which can be thoroughly used at −20°C.

The weldable 12Cr seamless linepipes were shipped for the first time in the world in 1996, and have been delivered to date in total amount of more than 20 000 t.

3.8 Premium Connection "KSBEAR"

The use of premium connection with metal-to-metal seal is becoming the general practice for OCTG. However, since inclined or horizontal wells are increasing in number in recent years, there have also been an increasing the number of well designs in which the existing specialty joints are not suitable. In particular, the threaded connections with high leak-resistance in compressive load, external pressure and bending environments have been desired. In response to these market needs, JFE Steel developed a premium threaded connection for OCTG, KSBEAR, with leak-resistance under high compression load, bending moment, and external pressure.

3.8.1 Performance requirements for OCTG connections

(1) Leak Resistance in Oil Wells

During and after installing OCTG in the well hole, threaded connections are subject to tensile force due to the dead weight of the tube. External pressure from the hole wall and internal pressure generated by the produced fluid also act on the joint. In horizontal wells, curved parts are subject to bending, and compressive loads act on the inner radius of the bend, while tensile force acts on the outer radius. Resistant to leak is required for these various conditions.

(2) Ease-of-use of Threaded Connection

Threaded connections must have an anti-galling property when tightened multiple times. To shorten the time required in running work, prevention of cross threading and high work efficiency are required.

3.8.2 Features of KSBEAR

The design of the KSBEAR joint is shown in **Fig. 20**.

(1) Adoption of Negative Load Flank Angle on Thread

Adoption of negative load flank angle on thread greatly reduces the forces which attempt to separate the pin thread and coupling thread in the tube radial direction when tensile, external pressure and bending forces simultaneously act on the tube.

(2) Optimization of Stabbing Flank Gap

Optimization of stabbing flank gap lightens the loads on the seal part and shoulder part, greatly reducing plastic deformation of the shoulder and seal through the contact of stabbing flanks when a high compressive load acts on the joint. Leak resistance under tensile load after compression is consequently improved.

(3) Optimization of Corner Radius of Pin Load Flanks

To prevent galling, the corner radius at the top of the pin load flanks is increased to disperse stress.

(4) Optimization of Load Flank Angles of Pin and Coupling

The angle of the pin load flank with respect to the coupling was changed. This causes stress to concentrate at the bottom of the pin thread, where strength is highest, improving anti-galling performance.

(5) 25° Stabbing Angle

The stabbing angle, which was 10° in the buttress modified connection, was increased to 25°, improving work efficiency during joint makeup.

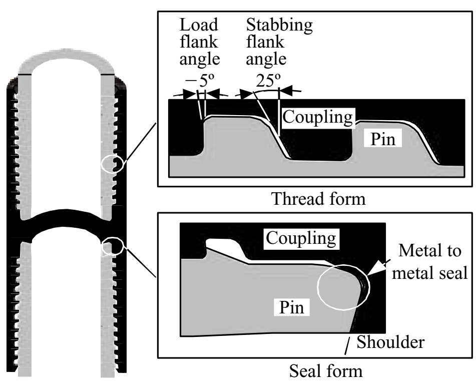

Fig. 20 Design of KSBEAR

Table 10 Grade, size and interference of specimen

Grade	Size	Interference*			
13CR-80	5-1/2”×23.0 1b/ft	H/H	H/L	L/H	L/L
13CR-80	7”×29.0 1b/ft	H/H	H/L	L/H	L/L
13CR-80	7”×35.0 1b/ft	H/H	H/L	L/H	L/L

* Thread/Seal
H : High, L : Low

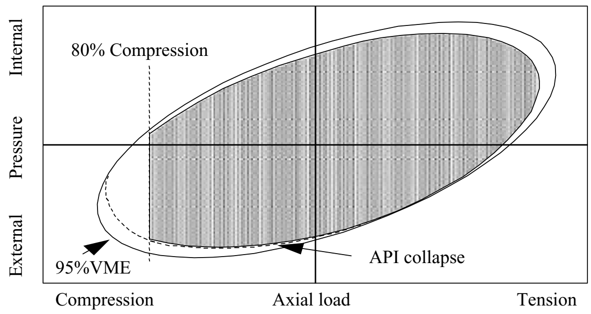

Fig. 21 Performance of KSBEAR

3.8.3 Performance evaluation test of KSBEAR

An example of the test method and test results required by a certain oil major company are described below.

(1) Test Method

The grade, size and interference of specimens are shown in **Table 10**.

(a) Green dope (environment-friendly lubricant) applied in screw tightening
(b) Bending test at 19.7°/30 m
(c) Compression test at 80% PBYS (pipe body yield strength)
(d) 100 cycles in heating cycle test
(e) Simultaneous compressive and bending loads, simultaneous tensile and bending loads
(f) Tightening test after completion of leak test

(2) Test Results

No leakage was detected in the various tests mentioned above, and no galling was observed when the thread and seal parts were inspected after tests. Thus, the KSBEAR displayed stable performance without leakage under the severe conditions of compression at 80% PBYS shown in **Fig. 21**.

3.9 Ultra-thin Wall Tubes

For application-related reasons, high strength, thin wall thickness and smooth surface are required to steel tubes for high pressure gas vessel. These requirements are expected to become stricter in the future with increasing demand for CNG vessel for automotive use.

To satisfy these requirements, JFE Steel's seamless tubes are manufactured using a thin wall pipemaking technology and a surface property smoothing technology which are distinctive features of these JFE Steel products (**Fig. 22**).

The tubes for high pressure gas vessel (**Photo 3**) have the ratio of wall thickness to outer diameter of the order of 2%, and are the thinnest-walled products in the field of seamless tubes. Since the thin wall seamless tubes require an extremely high level of manufacturing technology from the viewpoint of dimensional accuracy, JFE Steel has adopted an optimum rolling schedule for preventing eccentricity and wall thickness deviations caused by the piercing process.

To improve inner surface properties, it is necessary to prevent rolled-in scale caused by the inner tool (plug) during rolling. For this, JFE Steel adopted an optimum scheduling method, which makes it possible to minimize temperature drop in the rolled material, and a lubricant for thin wall material.

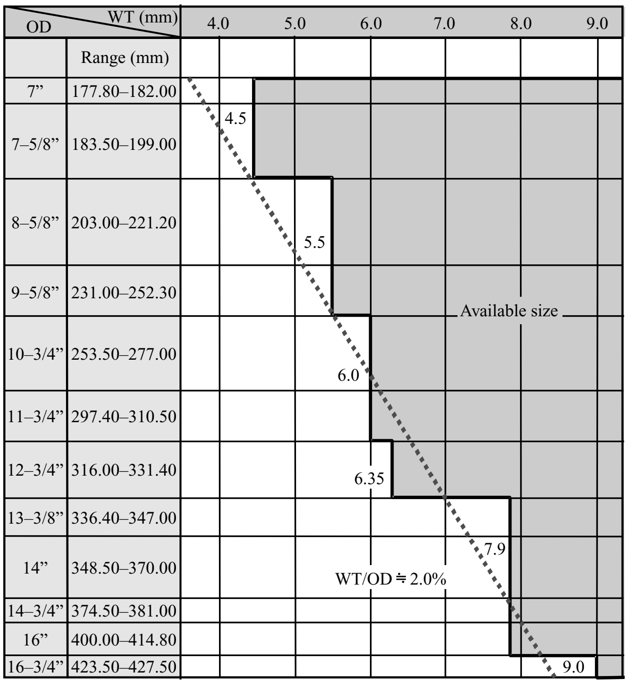

Fig. 22 Available manufacturing size

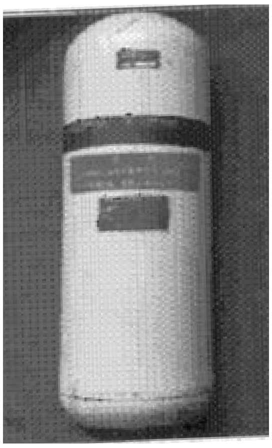

Photo 3 Vessel for high-pressure gas

3.10 Corrosion-resistant Pipe with Outer Coating of Non-PVC Resin for Gas Use "PLS-F"

Recognizing a heightened social responsibility for the global environmental problem of environmental pollutants originating in the treatment of waste materials containing polyvinyl chloride resin (PVC), JFE Steel has been developing substitutes for PVC-coated pipes in its line of corrosion-resistant coated pipes. As an example, the company developed a polyethylene-coated steel pipe, PLS-F, for use in passages through fireproof partitions as a substitute for the PVC-coated pipe in gas piping applications.

3.10.1 History of approval

In the past, only PVC-coated steel pipes, which have a self-extinguishing property, were approved for use in piping work in "fireproof partitions" in apartmenthouses, condominiums, office buildings and so on under the provisions for heat resistant performance in the Building Standards Act and Fire Services Act. However, following a review of evaluation standards in 2001, approval is now possible for pipes coated with polyethylene which is a flammable material, provided proper heat resistance and weathering resistance are imparted to the resin. This has expanded the range of possible uses to include not only conventional underground applications but also exposed piping.

The composition of the product coating is shown in **Fig. 23**. A photograph of typical products is shown in **Photo 4**.

3.10.2 Product features

The PLS-F offers the following three advantages:

(1) Non-PVC resin coating (Polyethylene is used)
(2) Piping locations: Can be used underground, in uptakes (meters), and indoors (general, passages through fireproof partitions, areas around kitchens)
(3) Pipe connection method: Threaded joint, mechanical joint

3.10.3 Rating for fireproof partition passages

Certified under Fire Protection Equipment and Safety Center of Japan

Rating No.: 14-654

Approval by Minister of Land, Infrastructure and Transport

Approval No.: Walls) PS060WL-0059
Floors) PS060FL-0060

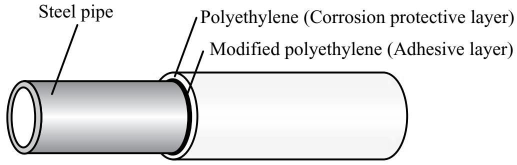

Fig. 23 Construction of coating for "PLS-F"

Photo 4 "PLS-F"

4. Conclusion

In response to the problem of global warming, a variety of new energy sources, represented by hydrogen, are now in the technical development stage. High performance, high quality steels will play an indispensable role in achieving wide practical application of these new forms of energy. Moreover, when attempting to harness hydrogen energy, new properties will be required from the viewpoint of safety.

JFE Steel is contributing to the sustainable growth of society in energy and other fields by technical development and supply of high performance steel products which establish the standard for the times.

References

1) Yuga, M. et al. Yosetsu Kozo Symp. 2002 Koen Ronbun-shu. 2002, p.303–310
2) Matsui, K.; Omori, T.; Miyata, S.; Takemura, M. High performance steel for bridge construction. NKK Technical Report. no.165, 1999, p.11–16.
3) Tanigawa, O.; Ishii, H.; Itakura, N.; Amano, K.; Nakano, Y., Kawabata, F. The 420 MPa and 500 MPa yield strength grade steel plates with excellent HA2 toughness produced by TMCP for offshore structure. Kawasaki Steel Giho. vol.25, no.1, 1993, p.13–19.
4) Hisata, M.; Miyake, T.; Kawabata, F. 420 MPa yeild strength steel plate with superior fracture toughness for arctic offshore structures. Kawasaki Steel Giho. vol.30, no.3, 1998, p.142–147.
5) Araki, K.; Kohriyama, T.; Nakamura, M. Development of heavy section steel plates with improved internal properties through forging and plate rolling process using continuous casting slabs. Kawasaki Steel Giho. vol.30, no.3, 1998, p.181–185.
6) Araki, K.; Deshimaru, S.; Kondou, H.; Kohriyama, T. Manufacture of heavy section steel plates with improved internal properties through combined forging and plate rolling process using continuous casting slabs. J. of High Pressure Inst. of Jpn. vol.41, no.4, 2003, p.20–27.
7) Engo, S. et al. Proc. of Pipe Dreamers Conf. Yokohama, 2002-11, p.273–288.
8) Kondo, J. et al. Proc. of the 4th ISOPE Conf. Kobe, 1994.
9) Kobayashi, H. et al. Control of centerline segregation of continuously cast slabs by a new soft reduction method. CAMP-ISIJ. vol.2, no.4, 1989, p.1158.
10) Tanabe, H, et al. Tetsu-to-Hagané. vol.66, 1980, S-258.
11) Itadani, M. et al. Development of seam heat treatment process in ERW linepipe (heavy-wall large diameter ERW linepipe for sour service-2). CAMP-ISIJ. vol.7, no.3, 1994, p.747.
12) Kawabata, F. et al. Toughness and wet-H_2S resistance of heavy-wall large diameter ERW linepipe (heavy-wall large diameter ERW linepipe for sour service-1). CAMP-ISIJ. vol.7, no.3, 1994, p.746.
13) Kami, C. et al. Effect of chemical composition and hot rolling condition on strength and toughness in hot rolled steel sheets for electric resistance welded pipe. CAMP-ISIJ. vol.15, no.6, 2002, p.1221.
14) Kimura, Y. et al. Corrosion/94 paper. NACE. no.18, 1994.
15) Morioka, N.; Oka, H.; Shimizu, T. Development of manufacturing technology for high alloy steel seamless pipe by Mannesmann process. Kawasaki Steel Giho. vol.29, no.2, 1997, p.57–63.
16) Yorifuji, A.; Toyooka, T.; Kanayama, T. Techniques for extending life of tools for piercing high Cr stainless steel seamless pipes in Mannesmann type piercer. Kawasaki Steel Giho. vol.29, no.2, 1997, p.64–70.
17) Tamaki, K. Corrosion/89 paper. NACE. no.469, 1989.
18) Kimura, Y. et al. Corrsion/97 paper. NACE. no.22, 1997.
19) Miyata, Y.; Kimura, M.; Murase, F. Development of martensitic stainless steel seamless pipe for linepipe application. Kawasaki Steel Giho. vol.29, no.2, 1997, p.90–96.