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Steel Products for Shipbuilding†

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Abstract:

Product designs and properties of 6 steel products for shipbuilding are described. They are new TMCP (thermo-mechanical control process) steel plates, weldable with high heat input, for container ships and LP (longitudinal profile) plates, both contribute to the increase in productivity at shipyards through the large reduction of welding time, anti-corrosion steel plates for crude oil tankers NAC5 which contribute to high performance of ships from the viewpoint of corrosion, cladded steel plates for chemical tankers, anti-corrosion pipes, JFE-MARINE-COP, used in crude oil tankers for loading and unloading crude oil, and shapes for shipbuilding which are produced using TMCP to realize weldability as good as steel plates.

1. Introduction

In recent years, the shipbuilding industry has energetically promoted high performance of ships and improved productivity in construction in response to vessel diversification (trend toward exclusive-use ships). In the process, the industry has also pointed out a variety of developmental needs related to steel products, resulting in the creation of new technologies and new products.

This report describes the product design concepts and properties of the following 6 products which were developed by JFE Steel in response to these needs. In the field of plate, they include new TMCP (thermo-mechanical control process) steel plates for high heat input welding for container ships, which contribute to improved productivity by greatly reducing welding working time, and LP steel plates (longitudinally profiled plates, also called taper plates), new anti-corrosion steel plates for crude oil tankers, NAC5, which contribute to higher performance in ships through improved corrosion resistance, and clad steel plates for chemical tankers. Tubular products include JFE-MARINE-COP for crude oil tankers, which improves corrosion wear performance in onboard oil receiving pipes used in loading and unloading crude oil. Among shape steels, JFE Steel has developed TMCP technologies for shapes for shipbuilding which provide weldability equal to that of plates.

2. Steel Plates

2.1 Steel Plate for High Heat Input Welding "EWEL"

With the increase in long distance freight transportation in recent year, the size of container ship has been enlarged rapidly, and even 8 000 TEU (TEU: twenty-feet equivalent unit) class container ships are being constructed recently. To construct such large-scale container ships, high strength and thick steel plates are used, such as 390 N/mm^2 class yield strength and maximum thichness of 65 mm or more. For welding of these thick plates, 1-pass vertical electro gas arc welding (EGW),

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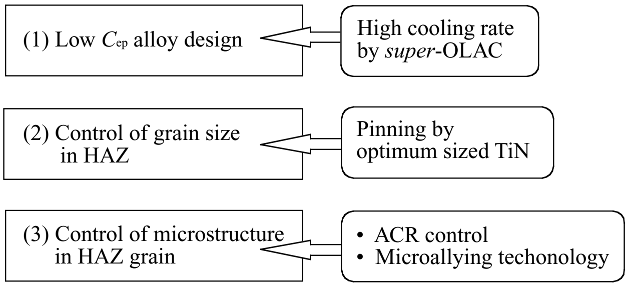

Fig. 1 Concept of developing high strength steel plates, "EWEL", for high heat input welding

which has high welding efficiency, has been applied, and the heat inputs in these welding reach ultra-high level exceeding 400 kJ/cm. This high heat inputs cause the remarkable coarsening of microstructure in heat affected zone (HAZ), and greatly decrease the toughness of welded joint. Furthermore, in order to meet the requirements of higher strength and increased thickness, it is necessary to increase the carbon equivalent (C_{eq}) and/or to add alloying elements, but this causes deterioration in weldability and the toughness of welded joint.

To resolve these problems, JFE Steel developed a high heat input welding technology based on the technical concept shown in **Fig. 1**, resulting in steel plates for high heat input welding, EWEL, which is used in large-scale container ships and other applications.[1)] In EWEL, excellent base metal properties and welded joint properties are realized by the combination of three concepts:

(1) Low Carbon Equivalent Alloy Design of the Base Metal

By applying the high cooling rate attained by JFE Steel's *Super*-OLAC (on-line accelerated cooling) technology, the optimum composition design is prepared considering the strengths of both base metal and welded joint, and yield strength of the 390 N/mm^2 class is achieved at the same C_{eq} level as in YS355 N/mm^2 class steel, and also, the upper bainite, which is detrimental to the toughness of welded joint, is suppressed.

(2) Control of Grain Size in HAZ

By using optimum TiN, refinement of the grain size in the HAZ is achieved.

(3) Control of Microstructure in HAZ Grain

Nucleation of intra-granular ferrite is accelerated by applying ACR (atomic concentration ratio) control, which is JFE Steel's original technology, and other microalloying technologies.

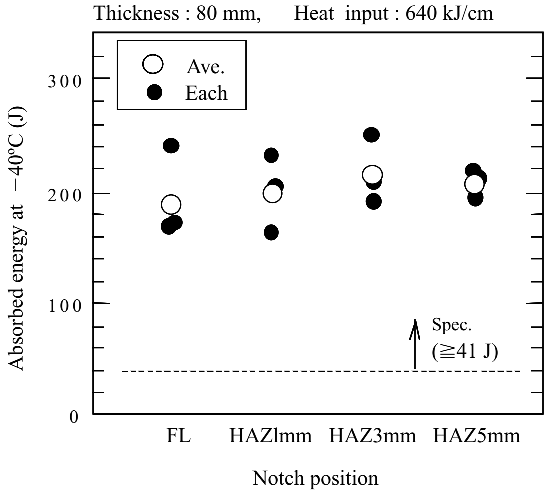

Fig. 2 Charpy impact energy of welded joint of EH40 plate

Figure 2 shows joint toughness in the case of 1-pass EGW of YP390 N/mm^2 class steel plates with a thickness of 80 mm. High heat input welding steel EWEL has excellent joint toughness even at −40°C.

F class high strength steel and low temperature service steel for hull structure, in which excellent low temperature toughness is required, were also developed and commercialized based on the same concept. In the welding of these steels, the heat input is not always high, but in the case of one side one pass FAB (flux asbestos backing) welding and FCB (flux cupper backing) welding, the equivalent heat input relative to the plate thickness is high, and excellent low temperature toughness is also required. **Table 1** shows an example of the welded joint toughness of a steel plate for low temperature service. Joints welded by FAB process (heat input: 88 kJ/cm) show superior impact toughness.

As is mentioned above, outstanding properties have been realized in the steel for high heat input welding EWEL by using the *Super*-OLAC and JFE Steel's advanced microalloying composition design to control the microstructure of the base material and HAZ. These developed steels have received an excellent evaluation from customers and have been adopted in numerous large-scale container ships, LPG ships, and others, and increasing demand is expected. It should be noted that JFE Steel has also applied the development concept of high heat input welding technology EWEL to the steels for bulding structure, and YS325–440 N/mm^2 class steels were developed and commercialized.[2)]

Table 1 Charpy impact energy of KL37 plate

Grade	Thickness (mm)	Welding method	Heat input (kJ/cm)	Charpy impact energy at −55ºC (J)					
				Fusion line		HAZ 1 mm		HAZ 3 mm	
				Min.	Ave.	Min.	Ave.	Min.	Ave.
KL37	17	FAB	88	70	128	74	116	264	289

2.2 New Anti-Corrosion Steel for Crude Oil Tankers "NAC5"

As illustrated in **Fig. 3**, the area under the upper deck in crude oil tankers is exposed to mixed atmosphere of exhaust gas and H_2S volatilized from the crude oil. As this area is also subject to cyclic condensation and evaporation of sulfur during day and night, a type of corrosion peculiar to the under deck area, called "vapor space corrosion", occurs. The average corrosion rate in vapor space is about 0.1 mm/y. However, considering the life of a crude oil tanker to be approximately 20 years, the possibility of deck plate replacement increases. Without replacement of deck plate which cost is very expensive, the resulting ship reliability may be lower.

JFE Steel developed a new anti-corrosion steel for crude oil tankers, NAC5 (New Anti-Corrosion No.5) that can extend the service life of deck plates by approximately 5 years, with the use of ship primer. NAC5 also has excellnt weldability, which is an essential property in shipbuilding materials. JFE Steel produces YS235–355 N/mm^2 class NAC5 plates and shapes in A and D grade.

Figure 4 shows a cyclic corrosion test results simulating the corrosion environment under the upper deck plate with NAC5 and conventional steel without shop primer. As for NAC5 without shop primer, the corrosion rates of both base metal and weld metal were approximately 10% lower than those of the conventional steel, which demonstrates the improved corrosion resistance. A cyclic corrosion test was also performed with cross-cut type specimens to investigate the life of the shop primer, with the results as shown in **Fig. 5**. Since the exfoliation rate of NAC5 was reduced approximately 40% in comparison to the conventional steel, shop primer remaining life can be extended by about two times with NAC5. Moreover, because the C_{eq} of NAC5 is reduced to the same level as that of the conventional steel by applying TMCP technology, conventional welding consumables can be used, and the NAC5 has weldability equivalent to the conventional steel.

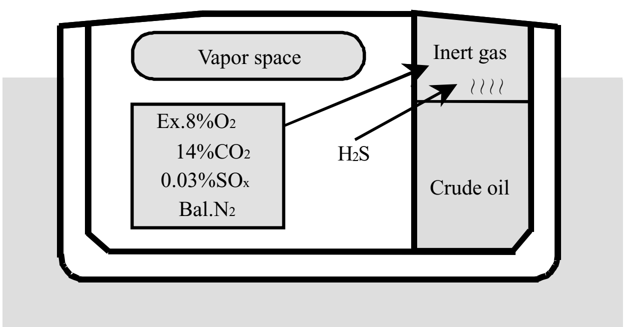

Fig. 3 Illustration of corrosion under upper deck plate in crude oil tanker

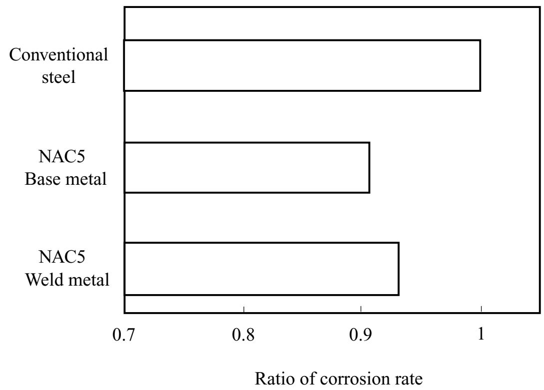

Fig. 4 Corrosion test results of NAC5 and conventional steel (Gas : CO_2-SO_2-H_2S-O_2-N_2, 720 h)

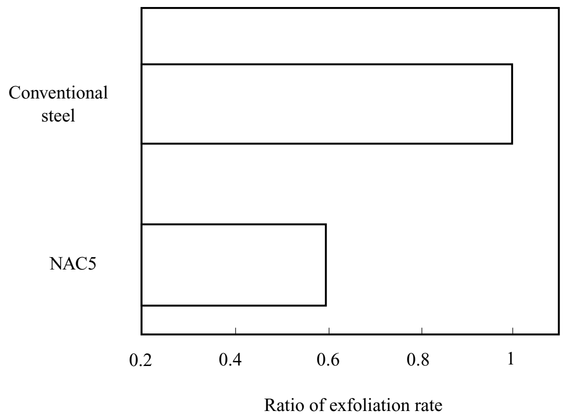

Fig. 5 Corrosion test results of cross cut specimens coated by shop primer

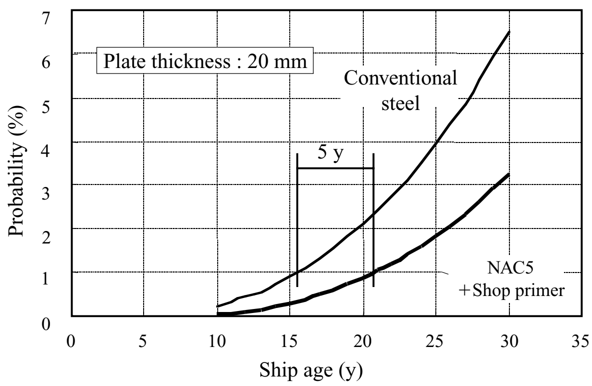

Fig. 6 Estimation of life of deck plate

Figure 6 shows an estimation of the service life of deck plates using NAC5 in comparison with the conventional steel based on an investigation of corrosion damage in the under surface of upper deck plate by Yamamoto.[3)] In the evaluation of 1% probability of deck plate replacement, the life of NAC5 deck plate with shop primer was estimated to be approximately 5 years longer than that of the conventional steel.

It is also considered possible to reduce maintenance costs and enhance ship reliability by using NAC5.

2.3 LP Steel Plates for Shipbuilding[4-6)]

LP steel plates are plates in which the thickness is changed continuously in the longitudinal direction, and are high performance plates which make it possible to reduce the number of welds and steel weight in structures.

Figure 7 shows typical profiles of LP plates used in shipbuilding. LP1 is an LP plate in which the thickness is changed longitudinally in one direction, while LP2 has isometric parts at the head and tail ends. A uniform plate thickness for welded joints can be obtained by specifying these isometric parts. In LP7 and LP8, the plate thickness is changed longitudinally in two steps in the same direction. These thickness differences are imparted in the LP plate manufacturing process by continuously changing the roll gap during rolling.

The effect of applying LP plates in shipbuilding is illustrated in **Fig. 8**, which shows the trans-bulkheads of a bulk carrier as an example. In trans-bulkheads, it is necessary to reduce the plate thickness from the ship bottom to the top. Conventionally, a large number of plates of varying thicknesses were joined by welding, as shown in Fig. 8 (a), to reduce the plate thickness as stress decreases with the aim of reducing weight. The number of welds can be reduced by applying differential thickness plates in these parts, as shown in Fig. 8 (b). Differential thickness plates are plates having two different thickness in the longitudinal direction. In contrast, LP plates are tapered in the longitudinal direction. Use of LP plates, as shown in Fig. 8 (c), enables further reductions in steel weight and in the number of joints.

Figure 9 shows an example of typical locations where LP plates are applied in vessels. In addition the trans-bulkhead, LP plates can be used in a number of other parts, such as the upper deck, bottom plates, etc. Under rules for classification of ships, it is possible to manufacture LP plates of 40 k (A, B, D grade) and 50 k (A, D, E grade) class steel for shipbuilding.

Figure 10 shows JFE Steel's LP plate supply record since 1993 and improvements in the LP plate profile. Initially, only uni-directional LP plates were available, but more recently, bi-directional LP plates (1996), 8/1000 taper ratio LP plates (maximum taper ratio:8 mm/m; 2000), and 2-step LP plates (2001) have been developed.

Between 1993 and 2002, JFE Steel shipped more than 58 000 t of LP plates, and has steadily increased its supply record since these plates were first used in shipbuilding in 1993. In particular, use of LP plates has increased dramatically since 1999, showing that these plates are now widely recognized as materials which reduce the number of welds and steel weight when applied in shipbuilding, contributing to reduced construction costs. In one actual example, approximately 2 500 t of LP plates were used in a 170 000 t class bulk carrier, achieving a 700 m reduction in the length of welds and 218 t reduction in the weight of steel consumed.

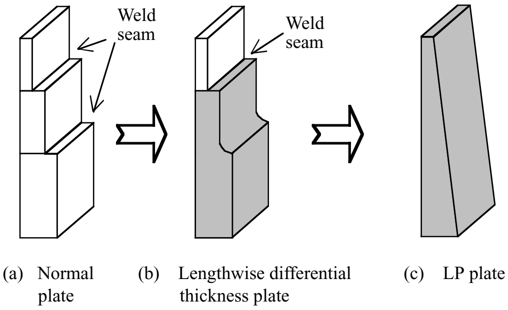

Fig. 8 Example of an omission of weld seams and reduction of weight by using LP plate

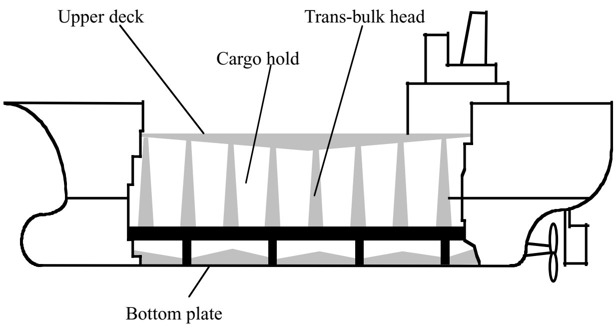

Fig. 9 Examples of typical application of LP plate for shipbuilding

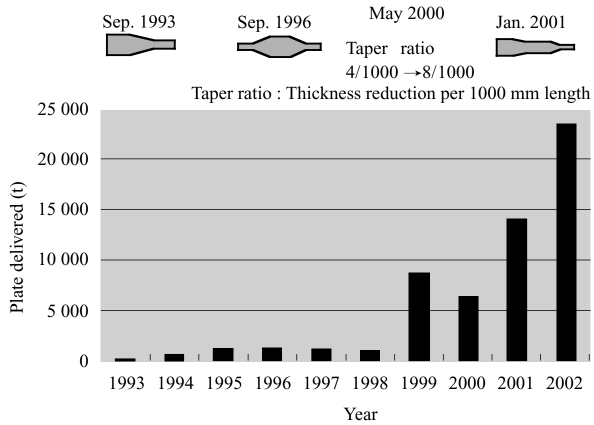

Fig. 10 Supply record of LP steel plates for shipbuilding

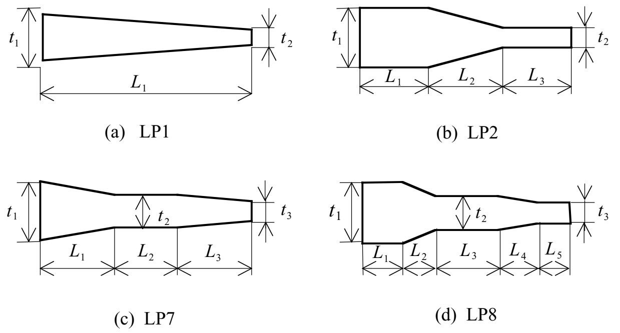

Fig. 7 Various thickness profiles of LP plates

2.4 Clad Steel for Chemical Tankers

Clad steel is a type of composite steel plate in which stainless steel plates or other material (called cladding or clad material) is bonded to one or both sides of a carbon steel or low alloy steel plate (base material). Accordingly, while clad plates possess the strength required in structural members (function of base material), they simultaneously have corrosion resistance or other functions (function of cladding), and are therefore a high performance material with properties which would be difficult to realize in a single material.

Recent years have seen an increasing number of cases in which stainless clad plates were used as hull material for chemical tankers (**Fig. 11**). The cladding (stainless steel) of stainless clad plates for chemical tankers is required to provide corrosion resistance against numerous kinds of chemical cargos, while the base material (carbon steel) must have excellent mechanical properties capable of withstanding high specific gravity and severe loading conditions. Furthermore, because stainless steel for bulkhead use is frequently welded during construction without removing the cladding, bonding strength between the base material and cladding is also required. Thus, among the applications of clad plates, chemical tankers have extremely high performance requirements.

Although various manufacturing processes can be used to produce clad plates, JFE Steel uses the rolling cladding process. The following describes some of the outstanding properties of rolled clad plates.

The results of an accelerated corrosion test of the cladding of clad steel plates are shown in **Table 2**. Pitting corrosion resistance, intergranular corrosion resistance, and SCC resistance all display the same level of performance as solid stainless steel materials. **Table 3** shows the results of an evaluation of corrosion resistance against crude phosphoric acid and sulfuric acid, which are representative examples of particularly strong chemicals among actual cargos. Although the test temperatures were set high, at 75°C and 50°C, respectively, for the accelerated corrosion test, satisfactory corrosion resistance was observed.

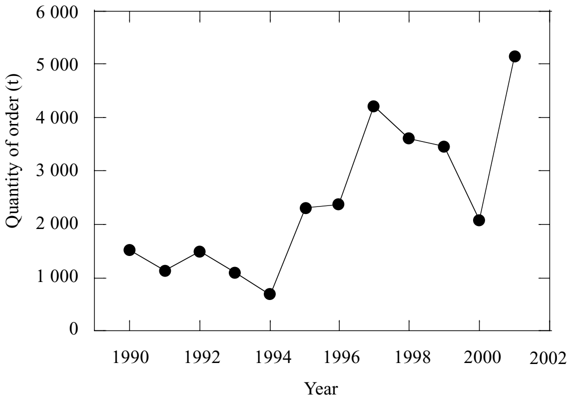

Fig. 11 Change in quantity of order of clad steel plates for chemical tankers

Table 2 Corrosion resistance of stainless clad steel

	Pitting corrosion JIS G0578 50°C, 24 h (g/m^2h)	Intergranular corrosion JIS G0575 16 h, 1t-bend	SCC (U-bend) Boiling 20%NaCl 500 h, 8t-bend
KA+316L	27.1 24.1 Ave. 25.6	No crack	No crack

(KA : Mild steel for shipbuilding)

Table 3 Corrosion rate in phosphoric and sulfuric acids

	Phosphoric acid 75°C (mm/y)	98%sulfuric acid 50°C (mm/y)
KA+316L	0.160 0.158	0.25 0.25

Phosphoric acid : $44\%P_2O_5 + 8.3\%SO_4^{2-} + 1.6\%Fe^{3+} + 0.8\%Al^{3+} + 1.3\%F^- + 0.2\%Cl^-$

Table 4 Tensile test and V-notch Charpy impact test results

	Tensile test*			Impact test**
KA+316L t=(9+3)mm Direction : T	YS (MPa)	TS (MPa)	El (%)	$vE_{-20°C}$ (J)
	276	473	34	82

* Full thickness, W=25 mm, Gauge length=200 mm
** 3/4 size V-notch Charpy impact test of base metal

Table 5 Bend test results

	Bend test*		
KA+316L t=(9+3)mm Direction : T	Face bend r=1.5 t	Root bend r=2.0 t	Side bend r=2.0 t
	Good	Good	Good

*JIS G 0601

As an evaluation of mechanical properties, **Table 4** shows the results of a full thickness tensile test of the clad steel and Charpy impact test of the carbon steel base metal, and **Table 5** shows the results of various bending tests. Sufficient properties for use as material for hull construction were observed in all the test results.

Rolled clad steels are considered capable of meeting the requirements of high performance materials, as outlined above, including those of further growth in demand in the future.

3. Steel Pipes

3.1 Cargo Oil Pipe for Crude Oil Tankers "JFE-MARINE-COP"

Because the onboard piping of oil tankers which is used to load and unload crude oil and seawater, called cargo oil pipes, is exposed to a seawater environment containing crude oil on both the outer and inner surfaces, painted 400 MPa class steel pipes (STPY 400) or Cr-added cast iron pipes are normally used. Moreover, in addition of resistance to seawater corrosion, cargo oil pipes must also have corrosion wear resistance. For this application, the company developed and brings to market a seawater-resistant pipe, JFE-MARINE-COP, which has both the equivallent weldability of 400 MPa steel pipe and the corrosion resistance and corrosion wear resistance of cast iron. The following describes the features and service performance of JFE-MARINE-COP.

3.2 Features of JFE-MARINE-COP

Table 6 shows the chemical composition and manufacturing process of JFE-MARINE-COP. Cu, Ni, and Cr are added to improve seawater corrosion resistance, and Ca is added to prevent preferential corrosion of welds. In the manufacturing process, controlled rolling and JFE Steel's on-line accelerated cooling device, *Super*-OLAC, are applied to secure a homogeneous bainite structure.

The corrosion rate in artificial seawater at 50°C tends to decrease as Cr addition is increased. As shown in **Fig. 12**, JFE-MARINE-COP with 1% Cr addition shows a corrosion rate of around 50% that of 400 MPa class steel without Cr addition.

Figure 13 shows the appearance of cross-sections of a JFE-MARINE-COP pipe used for 3 years as a cargo oil pipe in an actual vessel (named the Benetia). Virtually no thickness reduction attributable to general corrosion or local corrosion can be observed in either the pipe base metal or weld metal. This is a result of suppression of preferential corrosion of the HAZ by the homogeneous microstructure of the base metal/HAZ and addition of Cu, Ni, and Ca.

Further, no weld cold cracking was observed in low carbon JFE-MARINE-COP in a y-groove weld cracking test (Tekken test), even without preheating (**Fig. 14**).

Table 6 Chemical composition and manufacturing process of JFE-MARINE-COP

Chemical composition				Process
C (mass%)	Si (mass%)	Mn (mass%)	Others	
0.06	0.25	1.0	Cu, Ni, Cr	*Super*-OLAC

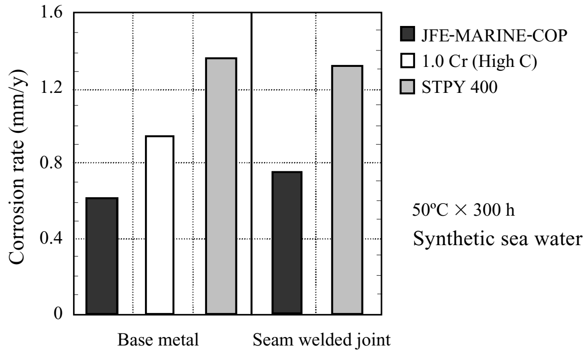

Fig. 12 Corrosion rate of JFE-MARINE-COP in synthetic sea water in comparison with those of 1% Cr, high C steel and STPY 400

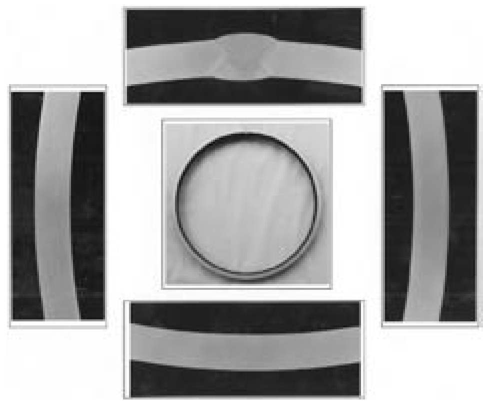

Fig. 13 Cross sections of the MARINE-COP after 3 years of service as a cargo oil tank in the BENETIA

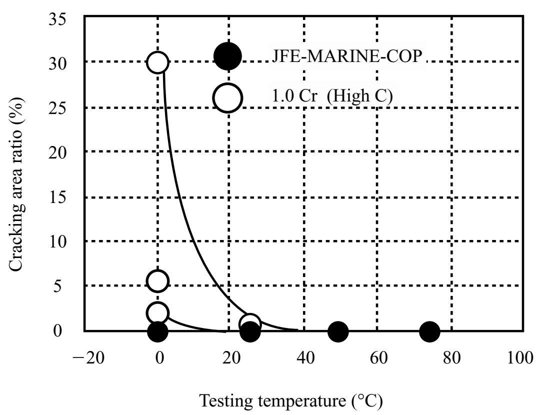

Fig. 14 Results of weld cold cracking evaluation test or Tekken test of JFE-MARINE-COP in comparison with 1% Cr, high C steel

Various welding consumables have been developed through joint research with Kobe Steel, Ltd. as consumables for circumferential welding of JFE-MARINE-COP, including manual welding (SMAW) with the brands mentioned below. Satisfactory corrosion resistance and corrosion wear resistance have been confirmed in welds using these consumables.

(1) LBK-52 for SMAW use
(2) MGK-52 for GMAW use
(3) TGSK-52 for TIG use

3.3 Manufacturing Results

JFE-MARINE-COP can be manufactured in outer diameters from 76.3 mm to 1 016 mm at JIS (Japanese Industrial Standards) STPY 400 and STPY 500 equivalent strength levels. JFE Steel currently produces around 5 000 t/y for customers inside and outside of Japan.

4. Steel Shapes

4.1 Shapes for Shipbuilding

JFE Steel and its group company, NKK BARS & SHAPES (NKBS) have developed products and processes for shapes for use in ship hulls since entering the shape steel business and were the first in Japan to manufacture representative shapes for shipbuilding such as unequal leg and unequal thickness angles (NAB) and bulb plates (BP). JFE Steel has established its leadership in shapes for shipbuilding by introducing equipment such as an exclusive-use shot blasting device for shapes and developing the first water cooling type TMCP technology for shapes. The following introduces JFE Steel's products and manufacturing technologies for shapes for shipbuilding.

4.2 Classification of Steel Shapes for Shipbuilding

4.2.1 Cross-sectional classification of steel shapes

The main shapes for shipbuilding produced by JFE Steel and NKBS are shown in **Table 7**. The JFE Steel Group has an extensive line of shape products for shipbuilding, including NAB, BP, unequal leg angles (ABS), flat bars (FB), and equal leg angles (AB). As available sizes, the JFE Steel Group also produces shapes with intermediate thicknesses outside JIS section dimensions, contributing to greater freedom in ship hull design and optimum design.

4.2.2 Available standards

NKBS has received manufacturing certification from major ship class societies for products up to DH36, and JFE Steel is certified for mild steel and high tensile steel up to EH40 applying TMCP technology, as introduced in the following section. JFE Steel has also received certification to manufacture low temperature service steels with guaranteed impact properties at −60°C for use in liquefied gas carriers and similar applications.

4.3 Manufacturing Processes for Steel Shapes for Shipbuilding

4.3.1 Rolling process for steel shapes for shipbuilding

Because shapes for shipbuilding, as represented by NAB, have an asymmetrical cross-section in the lateral and vertical directions, both the material property design, as mentioned above, and the manufacturing design in the hot rolling process are important. JFE Steel has realized high accuracy caliber rolling with 2-hi rolls by applying FEM analysis in addition to the caliber design technology which the company has accumulated over many years. The forming process in caliber rolling is shown in **Fig. 15** for NAB as a representative product.

4.3.2 TMCP for steel shapes for shipbuilding

JFE Steel has developed and applied non-water cooling and water cooling type TMCP technologies which meet the requirements of low C_{eq} high toughness, high strength steels with excellent weldability. TMCP technology was first developed as a plate manufacturing process. However, when applied to shape production, the

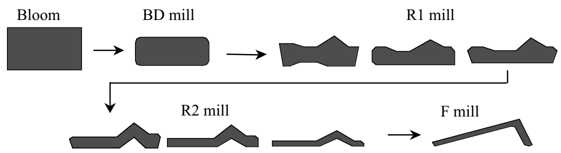

Fig. 15 Kaliber rolling process of NAB

Table 7 Dimensions of shapes for shipbuilding

Shape	No. of size	Section dimensions (mm)			Unit weight, W (kg/m)	Moment of inertia, I_X (cm^4)	Brand
		A×B	t_1	t_2			
NAB	28	200× 90 – 450×125	8 – 12.5	14–18	21.8 – 60.8	1 120 –16 600	JFE
BP	4	180 – 250	9.5– 12	–	16.5 – 29.9	671 – 2 360	JFE
ABS	6	100× 75 – 150× 90	7 – 12	–	9.3 – 21.5	118 – 619	NKBS
AB	30	20× 20 – 150×150	3 – 14	–	0.9 – 41.9	0.4 – 1 090	NKBS
	7	175×175 – 250×250	12 – 35	–	31.8 –128.0	1 170 – 9 110	JFE
FB	108	25 – 150	4.5– 25	–	0.9 – 29.4	–	NKBS

Table 8 Available TMCP shapes approved by certifying organization

Standard		Classification of ships							Chemical composition	
YP (kgf/mm^2)	Grade	NK	AB	LR	NV	BV	KR	CR	Steel	C_{eq} (LR)
32, 36	A, D	○	○	○	○	○	○	○	Si-Mn	≦0.36
	E	○	○	○	○	○	○	○	Si-Mn	
40	A, D	○	○		○	○	○	○	Nb	
	E	○	○		○	○	○	○	Nb	

○ : JFE has the general approval

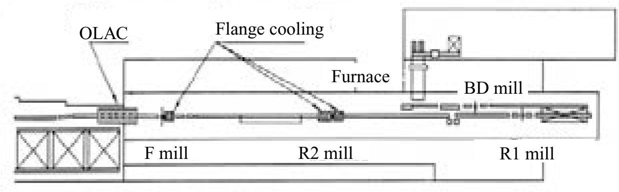

Fig. 16 Location of water cooling equipment

rolling conditions are subject to more difficult restrictions than with plates due to the complexity of the cross-sectional profile of shape steel and features peculiar to rolling with caliber rolls. Examples of these problems include the difficulty of securing homogeneous properties and dimensional shape accuracy in cross-sections containing differing thicknesses and the load capacity limitations of caliber rolls. Accordingly, JFE Steel successively developed and applied a proprietary non-water cooling type TMCP technology for steel shapes, followed by the first water cooling type TMCP technology for shapes.

(1) Water Cooling Type TMCP for Steel Shapes

In rolling asymmetrical NAB, the temperature of the flange is higher than that of the web during rolling and in finishing due to the cross-sectional profile (the flange is thick, whereas the web is thin). Accordingly, in the TMCP process for NAB, uniform strength properties are obtained through the entire cross-section by securing sufficiently rollimg reducing in the low temperature region of Austenite and/or in subcritical regin for the web and applying accelerated cooling after rolling.

(2) Cooling Equipment for Shape Steel TMCP

The arrangement of the cooling equipment for TMCP for shipbuilding steel shapes is shown in **Fig. 16**. For accelerated cooling after rolling, an OLAC device is installed after the finishing rolling mill, while flange cooling devices are installed in the guides at the intermediate and finishing mills to improve homogeneity in all parts of the product and enhance TMCP efficiency. The respective cooling devices are designed to enable temperature control considering the temperature characteristics of each part of the rolled material.

(3) Available Standards for TMCP

JFE Steel has received certification to manufacture low C_{eq} high strength steels by TMCP from leading certifying organizations, as shown in **Table 8**.

5. Conclusions

In response to the requirements of the shipbuilding industry, JFE Steel has developed and commercialized advanced products such as water cooled TMCP steels which have now become world-standard products. In the future, JFE Steel Group will continue to develop Only 1 and No. 1 products which meet the needs of the shipbuilding industry, for example, by contributing to higher productivity and higher performance, including ship collision safety, corrosion resistance, and fatigue resistance. Through the products mentioned above, JFE Steel will contribute to the development of society and protection of the global environment.

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