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High Performance Steel Plates for Shipbuilding —Life Cycle Cost Reduction Technology of JFE Steel—†

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Abstract:

This paper describes the product designs and properties of the newly-developed anti-corrosion steel plates and high fatigue property steel plates that are expected to reduce the life cycle cost (LCC) of ship. The anti-corrosion steel plates for crude oil tankers, "JFE-NAC5," enhance the exchange period of upper deck plates 5 years longer than the conventional steel plates due to the improvement of corrosion resistance and the extension of primer lifetime. The anti-fatigue damage steel plates, "JFE-AFD," show more than twice longer fatigue propagation life compared to conventional steel plates, as well as improving fatigue strength.

1. Introduction

With the increasing number of aging ships, damage of ship hulls caused by corrosion and fatigue has become a problem in recent years. Because hull life is determined mainly by the progress of corrosion and fatigue, rational repair based on an accurate assessment of remaining life and the development of materials with resistance to corrosion and fatigue are key issues for reduction of the life cycle cost (LCC) of operating ships.

In cargo oil tankers, the vapor space of the cargo oil tank is a severe corrosion environment containing a mixture of an inert gas (combustion exhaust gas) with which the space is filled to prevent explosions and H_2S evaporated from the crude oil[1)]. The upper deck back is exposed to this corrosive atmosphere, and corrodes under cyclical wet and dry conditions accompanying day and night temperature changes. In spite of the considerable number of cases in which ship structural parts must be replaced due to corrosion loss, quantitative knowledge of corrosion remains inadequate, and as a result, no established corrosion measures exist at present. In 1999, the Ship Research Panel No. 242 (SR242)[2)], was organized in the Shipbuilding Research Association of Japan as a project for elucidating the controlling factors and mechanism of corrosion in cargo oil tankers. JFE Steel, taking advantage of its extensive knowledge of low alloy corrosion resistant steels, developed and commercialized corrosion resistant steel, "JFE-NAC5" (new anti-corrosion No. 5), for upper deck plates of cargo oil tankers, which realizes excellent corrosion resistance when used in combination with a shop-primer.

On the other hand, because hull structural components are subjected to cyclic loadings due to waves, a fatigue crack initiates from the parts where have large stress concentrations (ex. weld toe or the parts with geometrical discontinuities) according to circumstances. Then the crack propagates and finally develops into penetration, causing serious accidents. From the viewpoint of reduction of LCC of ships, establishing the proper life design and safety factor for damage due to this type of fatigue, and how these are to be guaranteed, are important issues. On the occasion of the Ship Research Panel No. 245 (SR245)[3)], which began in 2001, moves began to appropriately evaluate remaining life from the initial defects supposed in welds based on the crack propagation performance of steel materials and rationally improve hull structural safety over the ship's life cycle. Recently, the various ship classification societies, including the Nippon Kaiji Kyokai (NK), Det Norske Veritas (DNV: Norway Ship Classification Society), and Lloyd's Register of Shipping (LR), have established new suffix

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symbols for steel products with excellent fatigue crack propagation properties. In response to these movements in the shipbuilding industry, JFE Steel developed and commercialized a steel plate, “JFE-AFD (anti-fatigue damage),” with excellent fatigue crack propagation performance.

This paper describes the product design concept and performance of corrosion resistant steels for the upper deck plates of cargo oil tankers and high fatigue strength steel plates for ship hull structural use which were developed in response to the above-mentioned need for LCC reduction in the shipbuilding industry, together with an evaluation technology for LCC reduction.

2. Corrosion Resistant Steel for Upper Deck Plates of Cargo Oil Tankers “NAC5”

2.1 Corrosion of Upper Deck Back in Cargo Oil Tankers

2.1.1 Condition of corrosion in actual ships

As shown in **Fig. 1**, the typical chemical composition of the inert gas in the vapor space of tankers is approximately 14%CO_2-8%O_2-0.03%SOx-N_2 bal. The temperature of the upper deck plates changes cyclically from a minimum of 5–25°C at night to 35–60°C during the day. It is considered that, as such, the corrosion reaction which occurs at the upper deck back is the same as the ordinary atmospheric corrosion reaction, and this is accelerated by SO_2 and the H_2S evaporated from the crude oil. Furthermore, elemental S is precipitated when iron oxide (FeOOH) exists in a atmosphere containing H_2S and H_2O. Because this precipitated elemental S is distributed in layers, the corrosion product tends to flake off easily. Thus, because the rust layer does not have a protective function, the corrosion rate is not inhibited by a protective layer of rust, and corrosion proceeds continuously.

2.1.2 Reproduction of corrosion environment in laboratory

A corrosion simulation system was produced

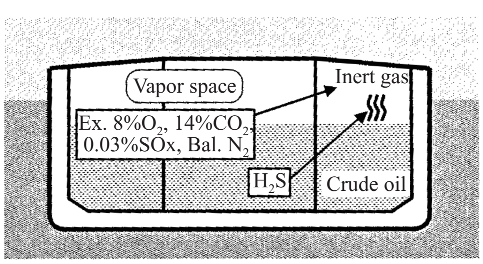

Fig. 1 Cross section of oil tanker and corrosive environment in crude oil tank

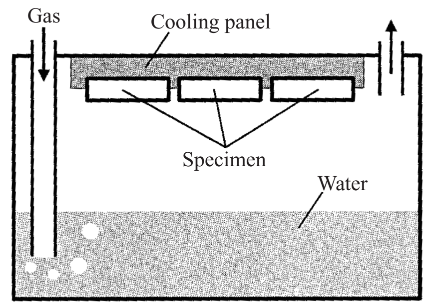

Fig. 2 Corrosion simulation system

in order to evaluate corrosion resistance in the corrosion environment of the upper deck back. Because the environment reproduced by this system conforms to the results of study in SR242, the corrosion mode and corrosion product conditions are in good agreement with those in the actual environment. The corrosion simulation system is shown schematically in **Fig. 2**. With the temperature and dew point in the test tank constant, a cyclical wet-dry environment was reproduced by changing the temperature of the test piece using a water-cooled panel. A mixed gas with a composition of CO_2-O_2-SO_2-H_2S-N_2 bal. was used to simulate a mixed atmosphere of inert gas and H_2S in the tanker vapor space.

2.2 Development of Corrosion Resistant Steel for Upper Deck Plates “NAC5”

2.2.1 Corrosion resistant alloy design of NAC5

NAC5 is a corrosion resistant steel which demonstrates effective corrosion resistance in the environment to which the upper deck back is exposed, as described above, and also possesses satisfactory performance as a steel product for shipbuilding in terms of mechanical properties and weldability. In the composition design, alloy elements which had the effects on corrosion resistance in the environment where elemental S was precipitated were considered, and a corrosion suppressing effect by extension of the life of the shop-primer applied as primary rust-proofing was also considered. In addition to an evaluation of uncoated materials, the corrosion resistance of shop-primer-coated materials was also evaluated. The test conditions were as follows.

Atmosphere: 12%CO_2 -5%O_2-0.01%SO_2-0.1%H_2S-N_2 bal.
Temperature: 30–50°C (Dew point: 40ºC)
Wet and dry cycle: Dry, 1 h-Transition, 3 h-Dewing, 1 h-Transition, 3 h
Test time: 720 h (30 days)

After the corrosion test, with the uncoated material, rust was removed and weight loss was obtained; with the primer-coated material, the primer was removed and the exfoliation rate of the primer from a cross cut was measured. The amount of corrosion and the exfoliation

Table 1 Chemical composition of NAC5

(mass%)

Grade	C	Si	Mn	P	S	Others	sol.Al	C_{eq}*
D32 (IACS)	0.14 ≦ 0.18	0.24 ≦ 0.50	1.02 0.90 /1.60	0.018 ≦ 0.035	0.005 ≦ 0.035	** ***	0.022 ≧ 0.015	0.33 ≦ 0.35

* C_{eq} = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15

** Alloy elements added.

*** Nb + V ≦ 0.12, Ti ≦ 0.02, Cu ≦ 0.35, Cr ≦ 0.20, Ni ≦ 0.40, Mo ≦ 0.08

IACS: International Association of Classification Societies

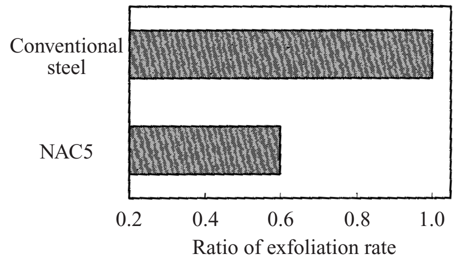

Fig.4 Corrosion test results of cross cut specimens coated with shop primer

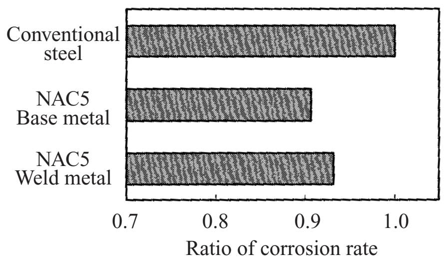

Fig.3 Corrosion test results of NAC5 and conventional steel (Gas : CO_2-SO_2-H_2S-O_2-N_2, 720 h)

rate of the primer were expressed as ratios relative to the conventional steel.

In studying the effects of alloy elements on corrosion resistance, the effective amount of addition was obtained for Cu, Ni, Cr, and other alloy elements. Finally, the composition was optimized considering not only corrosion resistance, but also the need to maintain the same levels of mechanical properties and weldability and minimize cost increases.

Table 1 shows an example of the chemical composition of NAC5. **Figure 3** shows the results of a corrosion test of the developed steel. With uncoated NAC5, it was found that corrosion of the base metal is reduced by approximately 10% in comparison with the conventional steel, and the corrosion resistance of welded joints is close to that of the base metal. Although conventional welding consumables were used, consideration was given to improving the corrosion resistance of welded joints by dilution of chemical components which are effective in improving corrosion resistance in the base metal.

Where the primer-coated material was concerned, as shown in **Fig. 4**, a reduction of approximately 40% in the exfoliation rate of the primer was observed. This shows that the exfoliation life of the shop-primer can be extended by approximately two times. In parts other than the cross cut, the remaining ratio of shop-primer with NAC5 was also higher. A corrosion test of welded joints in primer-coated materials was also performed, but local corrosion and exfoliation of the primer were not observed.

As described above, NAC5 is a corrosion resistant steel for upper deck plates which has a primer life extension effect. The upper deck life extension effect when NAC5 was applied in an actual ship is described in section 2.2.3.

2.2.2 Mechanical properties and welded joint properties of NAC5

The mechanical properties of NAC5 base metal and welded joints are shown in **Table 2**. Welded joints were prepared by coating the plates with Zn primer after shot blasting and performing one-side submerged arc welding (FCB welding), which is normally used as a welding method for upper deck plates, and their mechanical properties were evaluated. As all items satisfied standards, it can be understood that NAC5 possesses weld-

Table 2 Mechanical properties of NAC5

Grade	Thickness (mm)	Tensile test			Charpy impact test
		YS(MPa)	TS(MPa)	El(%)	$_VE_{-20}$ (J)
D32	25	375	502	28	202
(IACS)		≧ 315	440/570	≧ 18	≧ 31

$_VE_{-20}$: Absorbed energy at −20°C

Grade	Thickness (mm)	Welding method	Heat input (kJ/cm)	Tensile test		Charpy impact test				
				TS (MPa)	Fractured location	$_VE_0$ (J)				
						Weld metal	FL	HAZ1	HAZ3	HAZ5
D32	25	FCB	137	492	Base metal	163	126	110	102	89
(IACS)		–	–	≧ 440	–	≧ 34				

FL : Fusion line, HAZ1, 3, 5 : Heat affected zone of 1, 3, and 5 mm from fusion line

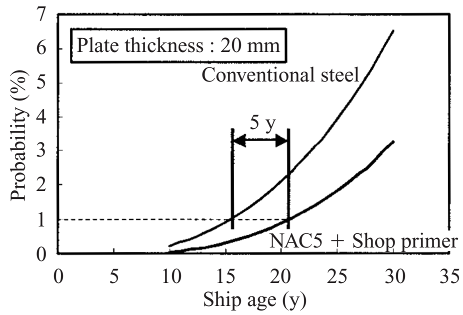

Fig.5 Estimated life of deck plate

ability equal to that of the conventional steel.

2.2.3 Prediction of upper deck life extension by application of NAC5

The hazard probability of the upper deck plate, in other words, the probability that repair will become necessary because the amount of corrosion loss in the upper deck plate exceeds the permissible value, was calculated using the Nippon Kaiji Kyokai database for changes over time in upper deck back corrosion and the results of an evaluation by the corrosion probability model proposed by Yamamoto[4]. **Figure 5** shows the results of a prediction of the life extension when NAC5 is applied in comparison with the conventional steel for a design plate thickness of 20 mm. Assuming that permissible corrosion loss is 20% of plate thickness, in other words, 4 mm in the case of a design plate thickness of 20 mm, and repair of the part becomes necessary when the corrosion loss exceeds 4 mm, the useful service period and hazard probability of the respective materials was obtained. Considering the fact that the primer life is extended by 2 years by the primer life extension effect of NAC5, in combination with the corrosion rate reduction effect achieved by the approximate 10% improvement in the corrosion resistance of the steel itself, it was estimated that the period to reach a hazard probability of 1% is extended by approximately 5 years by using NAC5. In other words, upper deck plate life can be extended by 5 years by applying NAC5.

2.3 Evaluation of Properties of NAC5 Applied to Tanker Bottom Plates

2.3.1 Bottom plate environment and simulated corrosion test

Because the corrosion mode in cargo oil tanker bottom plates is pitting, the corrosion environment is considered to be different from that of the upper deck back, where corrosion takes the form of general corrosion. The surface of the bottom plate is covered with an oil coat with the chemical composition of crude oil. In addition, the presence of seawater containing approximately 8% NaCl and accumulation of sludge consisting mainly of rust which has dropped from the upper deck back have also been confirmed. In parts where protection by the oil coat is lost for some reason, it is considered that macro cells are formed by the action of the seawater and the elemental S and FeS contained in the dropped rust, and as a result, pitting is initiated and progresses. According to a questionnaire survey mainly of Japanese ship owners conducted by SR242, the bottom plate surface in cargo oil tankers is uncoated (mill scale or shot-blasting) in 57% of cases, or is coated with tar epoxy (25%) or partially or completely coated with shop-primer (18%). With tar epoxy coating, there is a danger of severe pitting originating at defects in the coating. Therefore, at present, a “no paint” specification is applied in many cases in expectation of protection by the oil coat[2].

NAC5 is expected to show a corrosion resistance in the environment in bottom plates where H_2S and elemental S exist, also. In order to evaluate corrosion resistance in the corrosion environment affecting tanker bottom plates, a simulated corrosion test was attempted. The surface of the test pieces was shot-blasted and oil-coated, and the pieces were then immersed in artificial seawater held at 50°C. The solution was saturated with a mixed gas consisting of 5%O_2-10%H_2S-N_2 bal. The condition of pitting occurrence was observed after 60 and 120 days, and corrosion was compared by obtaining the weight reduction.

2.3.2 Effect of application to bottom plates

As a result of the simulated corrosion test, it was found that corrosion is reduced by approximately 15% in uncoated NAC5 in comparison with the conventional steel, but no significant difference in the occurrence of pitting could be observed by experimented in the short period in the laboratory. However, a survey of actual ships conducted by Mitsui O.S.K. Lines, Ltd. found that the number of pits in conventional steel coated with shop-primer is extremely small, at 1/20 or less, in comparison with uncoated conventional steel. Based on this, it can be expected to improve corrosion resistance and reduced pitting occurrence by applying NAC5, which has a primer life extension effect, to cargo oil tanker bottom plates when a shop-primer coating is used.

3. High Fatigue Property Steel Plate “JFE-AFD”

3.1 Fatigue Damage in Ship Hull Structures

Fatigue damage in ship hull structures are caused by various types of cyclic loadings including the action of waves, vibration caused by the engine and propellers, and changes in internal pressure due to load/ballast. In particular, because the cyclic loadings caused by waves

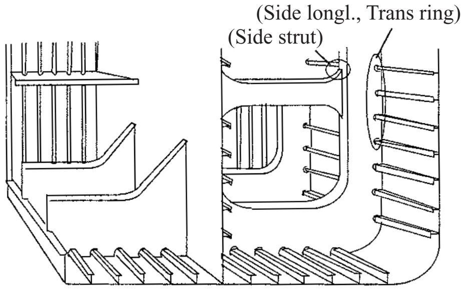

Fig. 6 Typical ship structure of single-hull tanker

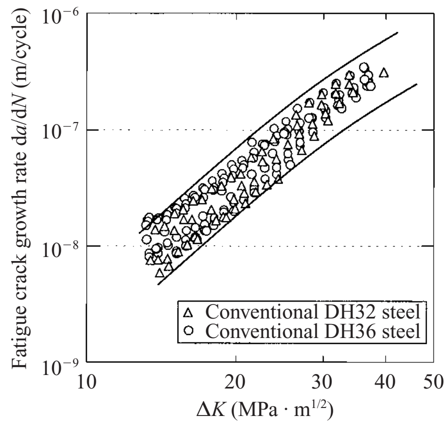

Fig. 7 Fatigue crack growth property of conventional YP32, 36 class steels

reach an average of roughly 10^8 cycles in 20 years of ship service, these are considered a main factor with a possibility of causing serious accidents in hull structural components. Taking the single hull structure shown in **Fig. 6** as an example, "Guidelines for Tanker Structures 2001," published by the Nippon Kaiji Kyokai[5] lists the intersection between vertical and horizontal members (side longl., trans ring) and the ends of side struts as the category of fatigue members/parts. In 1990s, a lot of fatigue damage occurred at these parts in single-hull very large crude carrier (VLCC)[6]. From a structural viewpoint, it is considerable that these types of damage may also occurred in double-hulled VLCC. Moreover, the area around slot openings in double-bottom floor plates is a part where attention has been given to the occurrence of fatigue cracking from the base metal. Steel plates with thicknesses of 15–25 mm are mainly used in these structural parts.

3.2 Study of Manufacturing Guidelines for High Fatigue Property Steel Plates

3.2.1 Fatigue crack propagation performance of conventional steels for shipbuilding

In the development of high fatigue property steel plates which contribute to improvement in the safety margin for fatigue damage, a study was conducted on the fatigue crack propagation performance of YP32 and 36 kgf/mm^2 steel plates for shipbuilding which are daily-produced. As a result, it was confirmed that the fatigue crack growth rates of these steel plates exist over a wide range, as shown in **Fig. 7**, in which the upper limit of the crack growth rate is approximately double that of the lower limit at that. Furthermore, it was also found that the steel plates with lower fatigue crack growth rates have performance on the same level with the steel plates recently approved by ship classification societies to use suffix symbols for fatigue crack propagation properties. Therefore a new high fatigue property steel plate was developed by the following technical concept.

3.2.2 Technical concept for improvement of high fatigue crack propagation performance

Firstly, it was decided that the chemical composition of the steel would not be modified, considering the fact that some conventional steel plates show satisfactory fatigue crack propagation performance. Major changes in the chemical composition might cause not only in changes base metal performance, including strength and toughness, but also deterioration of the welded joint performance (e.g. HAZ toughness, weldability). Because high fatigue crack propagation performance is secured mainly by control of microstructure, thermo-mechanical control process (TMCP) technologies, with JFE Steel's *Super*-OLAC (on-line accelerated cooling), were applied with high accuracy to control the fatigue crack propagation rate, which extends over a wide range, to the lower rate side. The development target values for the fatigue crack propagation rate were less than 1.5×10^{-8} m/cycle or at $\Delta K = 15$ MPa · m$^{1/2}$ and 7.8×10^{-8} m/cycle at $\Delta K = 25$ MPa · m$^{1/2}$. These target correspond approximately the central value or less in the data range for the conventional steel plates shown in Fig. 7.

Figure 8 shows the technical points for control of microstructure in order to improve fatigue properties. The first is achievement of fine grain structure. The number of grain boundaries, which have a function as

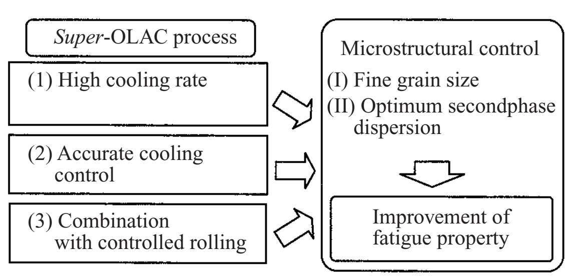

Fig. 8 Improvement of fatigue property by *Super*-OLAC

a barrier for crack propagation, is increased by refining the grain size using the *Super*-OLAC, which has a high cooling rate. The second is high accuracy control of microstructure to secure the optimum microstructure.

In addition to these points, the strength of the base material is also increased by refinement of the microstructure, improving both fatigue crack propagation properties and fatigue strength.

3.3 Performance of High Fatigue Property Steel Plate

Based on the product design concept described above, steel plates with high fatigue crack propagation performance were manufactured on production line with the optimized rolling and cooling conditions. A series of basic mechanical properties and fatigue properties (fatigue crack propagation properties and fatigue strength) of the steel plates and welded joints were investigated. Typical test results are described below.

3.3.1 Basic performance

Table 3 shows the chemical composition of YP36 kgf/mm^2 grade E class steel. The chemical composition is the same as the conventional steel plate of the same class. **Table 4** shows an example of tensile, bending, and Charpy impact test results. All test results show excellent performance, satisfying the standard values. Welded joint performance was evaluated by Charpy impact test of the weld metal and HAZ in FCB welded joints with welding heat input of 14.5 kJ/mm. Welded joints show superior impact toughness at all notch positions. Moreover, because the developed steel plate is manufactured using the same chemical composition as the conventional steel, sufficient weldability performance (welding cracking resistance) was also confirmed.

Table 3 Typical chemical composition

(mass%)

Grade	C	Si	Mn	P	S	C_{eq}*	P_{CM}**
EH36	0.12	0.35	1.32	0.015	0.004	0.35	0.20

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

Table 4 Typical mechanical properties of high fatigue property steel (Plate thickness : 25 mm)

Direction	Tensile test			Bending test (r = 1.5 t)	Charpy impact test	
	YS (MPa)	TS (MPa)	El (%)		$_{V}E_{-40}$ (J)	$_{V}T_{rs}$ (°C)
L	415	533	27	Good	205	−83
C	426	545	25	Good	156	−65
(IACS)	≧ 355	490–620	≧ 21	–	34 (L), 24 (T)	–

$_{V}E_{-40}$: Absorbed energy at −40°C
$_{V}T_{rs}$: Fracture appearance transition temperature

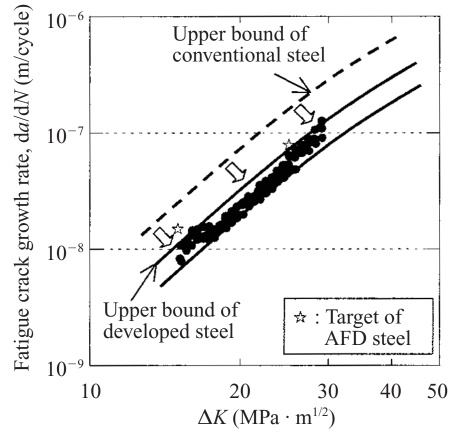

Fig. 9 Fatigue crack growth test result of high fatigue property steel

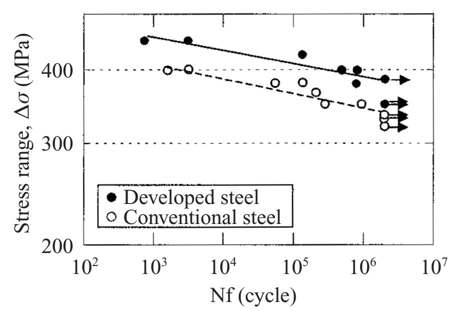

Fig. 10 Fatigue strength property

3.3.2 Fatigue properties

Figure 9 shows the results of fatigue crack propagation tests based on ASTM E647 procedure. The fatigue crack propagation tests were performed at room temperature in air using full-thickness compact test specimen. Superior fatigue crack growth rates which satisfied the development targets are confirmed. It was found that fatigue crack propagation performance can be controlled to the lower growth rate side consistently, in the comparison with the range of the conventional steels as shown in Fig. 7.

Figure 10 shows the results of a fatigue strength test of the developed steel plate and the conventional steel plate. The fatigue strength of the developed steel plate is improved corresponding to the strength increase obtained by refinement of the microstructure, as described above.

3.4 Current Fatigue Design Procedure and Fatigue Crack Propagation Simulation

The fatigue strength of ships is now evaluated based on the cumulative fatigue damage with 10^8 wave cycles, which corresponds to 20 years of ship service. The ship conditions used in evaluating fatigue strength are the normal sailing conditions in a fully-loaded condition and ballast condition. In the present, fatigue evaluation is performed by using the long-term frequency distribution of the hot-spot stress fluctuation and *S-N* curves by the linear cumulative damage law.

This evaluation method based on the cumulative fatigue damage makes it possible to predict the rough fatigue life related to the occurrence of cracking comparative easily. However, it cannot be applied to judgement of remaining life which is obtained by crack growth prediction from the detected crack size to the critical crack size. Therefore, it is not applicable to the remaining life judgment whether the ship can be kept in service until the next dry-dock inspection.

In response to this problem, "Progressive Fatigue Life Monitoring Method" and "Related Methods and Tools" were proposed in SR245[3,7] for the purpose of improving safety over the total ship life by utilizing a unified index from the design of each ship to sailing. In the Fatigue Life Monitoring System, the sea conditions encountered by the individual ship during service are designated by the monitoring system. The condition of fatigue in hull structural components is then tracked and determined using the history of sea conditions encountered and fatigue strength data including material properties in the design/manufacturing process, and remaining life evaluation is performed by crack propagation analysis using the crack length as a parameter. Here, a simulation of crack penetration life by the SR245 was carried out method using an example of the history of loads encountered in service between Japan and the Persian Gulf. The effect of the fatigue crack propagation properties of steel plates on the penetration life of flat parts with a surface crack-like defect was investigated. The results of this simulation are shown in **Fig. 11**. With both the conventional and the developed steel, the crack growth analysis was performed by the Paris Law[8], which uses coefficients obtained from the average values of fatigue crack propagation test results. Because the developed steel plate showed superior fatigue crack propagation performance, it shows more than twice longer fatigue propagation life compared to conventional

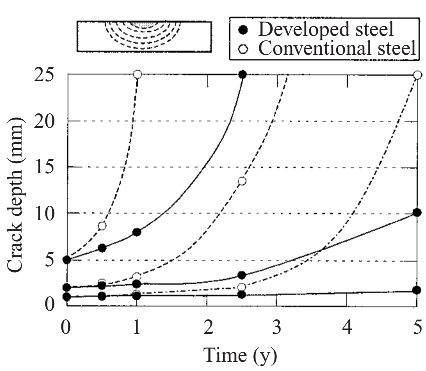

Fig. 11 Simulation of fatigue crack growth under service condition

Table 5 JFE Steel plate products for shipbuilding

Ship classification society standards		NK, AB, LR, NV, and other ship classification societies Mild steel/high strength steel/low temperature steel, etc. for hull structural use
	Steel plates for high heat input welding	JFE-EWEL
	Tapered plates	JFE-LP
	Corrosion resistant steel plates for cargo oil tankers	JFE-NAC5
	Anti-fatigue damage steel plates	JFE-AFD

NK: Nippon kaiji kyokai, ABS: American Bureau of Shipping,
LR: Lloyd's Register of Shipping, DNV: Det Norske Veritas

steel plates, as well as improving fatigue strength.

4. Conclusion

In response to the requirement for reduced life cycle costs (LCC) in ships, JFE Steel has developed two new steels for shipbuilding. From the viewpoint of corrosion, JFE Steel developed new corrosion resistant steel for the upper deck plates of cargo oil tankers, NAC5, and from the viewpoint of fatigue, a high fatigue property steel plate, JFE-AFD (anti-fatigue damage). In comparison with the conventional steel, NAC5 shows an improvement of approximately 10% in corrosion resistance, together with approximately double the conventional shop-primer life. Considering the combination of these two effects, the ship age when repairs become necessary due to wear of the upper deck plates are extended 5 years longer. NAC5 has already been adopted in four actual ships which are now in operation. Because JFE-AFD can provide more than double the conventional fatigue crack propagation life and also improves fatigue strength, it is expected to contribute to improvement of ship safety.

In the future, JFE Steel will continue to develop Only 1 and No. 1 products which contribute to higher functions and higher added value, and is committed to contributing to the development of society, including improved safety in ships. **Table 5** shows the steel plates for shipbuilding manufactured by JFE Steel.

In closing, the authors wish to express their thanks to Mitsui O.S.K. Lines, Ltd. for providing survey data on corrosion in actual ships.

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