World's first development and application of HTSS (high tensile strength steel) with yield stress of 47 kgf/mm² to actual ship hull structure

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Along with the rapid increase in the size of container ships, the steel plates used for ship hulls have been increased in thickness. As the toughness of steel plates generally tends to decrease for thicker plates, more consideration of brittle fractures is required. In order to address this challenge, Mitsubishi Heavy Industries, Ltd. (MHI) has jointly developed with Nippon Steel Corporation steel plates with the yield strength of 47 kgf/mm², which is an increase of about 20% in comparison with conventional steel plates for general commercial ship hulls. This steel possesses both high strength and high toughness, which has made it possible to substantially improve the reliability of the hull structure of mega container ships against brittle fractures through reduced plate thickness and appropriate plate layout design based on good use of its special characteristics. In addition, its weight-reducing effect has also contributed to improvement in propulsive performance and cargo loading efficiency. This steel has already been used for the first time in the world on an 8100 TEU container ship constructed by MHI and has gained the deep appreciation of the customer both for its safety and performance.

1. Introduction

As shown in **Fig. 1**, container ships have increased in size over the past 10 years, along with which the steel plates used have become thicker to cope with the increased load as a result of the enlarged hulls. Generally speaking, the thicker a steel plate is, the lower its toughness, and its resistance to brittle fracture tends to decrease. MHI together with Nippon Steel Corporation has worked on developing a highly reliable hull structure for mega container ships. As a result of these efforts, HTSS (high tensile strength steel) with a yield strength of 47 kgf/mm² has been developed which is an increase in strength by about 20% in comparison with the conventional steel plates and has been used on an actual ship as the world's first. Further, Nippon Kaiji Kyokai (Class NK) participated in the establishment of the relevant standards. This report introduces an outline of the ship in which the steel plates were used and their characteristics, as well as the concept of the safety design of the hull structure, and finally describes the welding method.

2. Introduction to the state-of-the-art 8100 TEU container ship

MOL Creation was constructed in MHI's Nagasaki Shipyard and Machinery Works for Mitsui O.S.K. Lines as the world's first 8100 TEU class container ship using 47 kgf/mm² HTSS and was delivered in June 2007 as the first ship in the six ship series of that class.

TEU: Twenty feet equivalent unit (used to indicate the size of container ship)

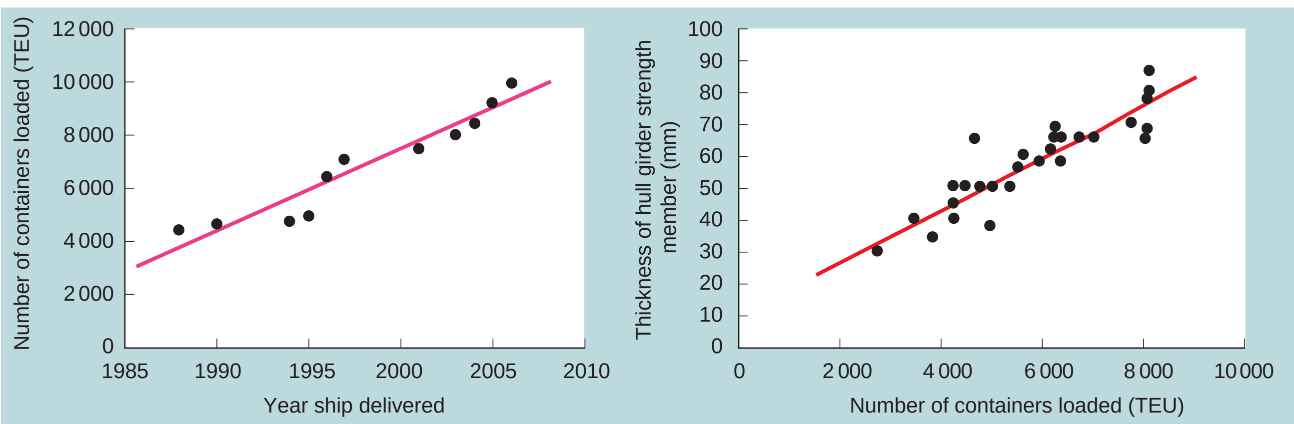

Fig. 1 Increase in size of container ships and increase in thickness of hull girder strength members

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An outline arrangement of this ship is shown in **Fig. 2** and its principal particlulars in **Table 1**. This is the shipowner's largest container ship, which is scheduled to serve on the Asia-Europe route after she is put into service.

This ship has widely adopted state-of-the-art technology including 47 kgf/mm^2 HTSS. The outline is as follows:

(1) The latest electronic control type Mitsubishi Sulzer 11RT-flex96C was adopted as the main engine. The adoption of electronic control has realized optimal fuel injection control in accordance with the engine revolutions, bringing about the excellent emission reduction of NOx (nitrogen oxides) and PM (particulate matter).

(2) With regard to propulsive performance, despite the fact that the fuel-efficient, 11 cylinder main engine is the smallest for this class of container ship, a service speed of 25.25 kt has been attained because of its sophisticated hull form.

(3) With regard to loading performance, reduced lightweight and a lower center of gravity were realized through the adoption of a relatively wide hull form and 47 kgf/mm^2 HTSS, which have contributed to an increase in the number of containers loaded and a reduction of the amount of ballast water. As a result, improved profitability and operational convenience have been brought about.

(4) All the fuel tanks and oil tanks are structured within a double hull to prevent marine pollution.

(5) Dangerous goods can be loaded into all holds. In particular holds Nos. 1 to 7 can take cars loaded with fuel.

As described above, this is a state-of-the-art container ship which has improved both environmental friendliness and safety through the use of the latest technology including 47 kgf/mm^2 HTSS.

3. Adoption of steel plates with yield stress of 47 kgf/mm^2 and improvement of safety

3.1 Material property

The history of the increase in strength of steel plates for hull structures is shown in **Fig. 3**. While conventional container ships normally use 40 kgf/mm^2 steel plates, an approximately 20% increase in strength has been realized by development of the 47 kgf/mm^2 HTSS. In developing these steel plates, both the increased strength and resistance to brittle crack propagation described in Sections 3.2 to 3.3 have been realized at the same time. Further, the high weldability integral to steel plates for shipbuilding work has been addressed by grain refining of the metal structure through precise control of the heating, rolling and cooling conditions (**Fig. 4**).

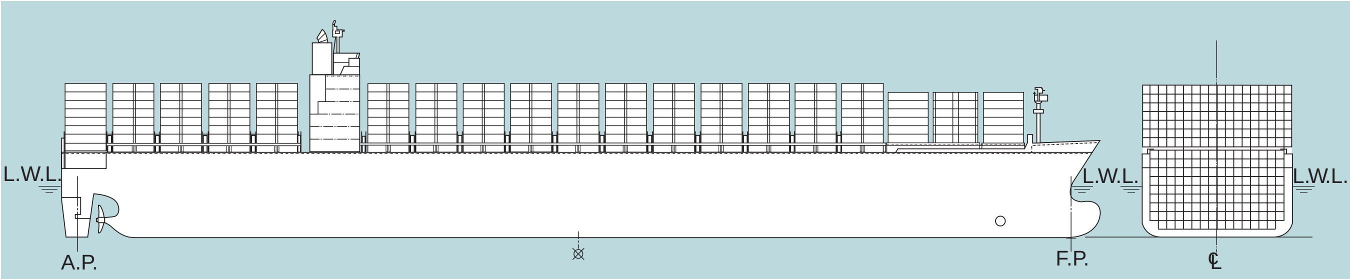


Fig. 2 General arrangement

Table 1 Principal specifications

Overall length (m)	Approx. 316	Number of containers loaded (TEU)	8 110
Breadth (m)	45.6	Main engine	MITSUBISHI-SULZER 11RT-flex 96 C
Full load draft (m)	14.5		
Dead-weight (t)	90 678	Max. output	62 920 kW × 102 rpm
Gross tonnage	86 692	Service speed (kt)	25.25

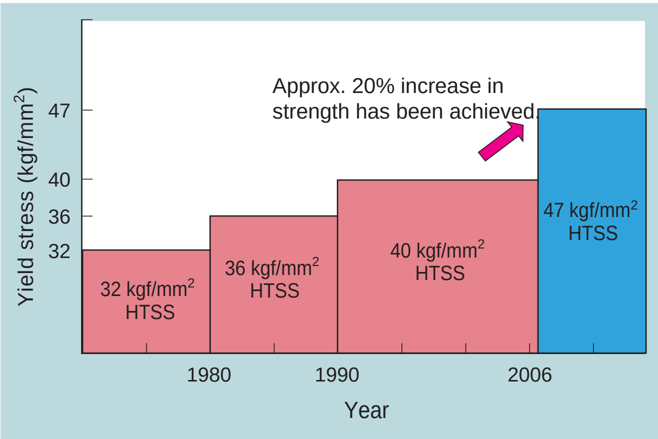
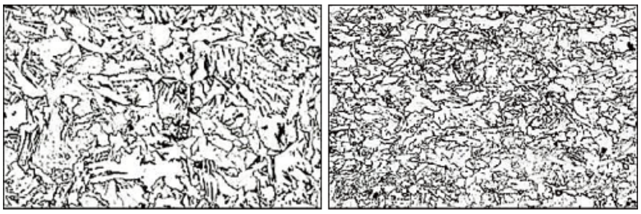


Fig. 3 History of maximum strength of high tensile strength steel used for hulls of general commercial ships



(a) Conventional steel (b) 47 kgf/mm^2 HTSS

Fig. 4 Comparison of microstructures (optical microscope structure)

3.2 Structural design

Container ships, as shown in **Fig. 5**, have a large opening, through which containers are loaded inside the cargo holds, on the upper deck of their hulls, where the arrangement of the structural members which resist the loads which bend the entire hull (longitudinal bending load (hull girder bending)) is limited. Therefore, as the upper hull is naturally subject to large loads, thick plates, usually of about 65 mm, have been used to cope with this problem. In addition, as the hull girder bending loads increase due to the growing size of ship hulls, increasing the plate thickness (80 mm to 100 mm) had to be further accelerated as shown in Fig. 1. However, this increase in thickness leads to a decrease in the toughness of the steel plates and can possibly reduce the reliability of the hull structure. In this regard, a hull structure is designed to arrest any brittle crack propagation which might occur in the worst case. This has been realized by considering the balance between plate thickness and the toughness of the ship hull. This includes the following concepts, and a large-scale model test, described in Section 3.3, was carried out to verify the effectiveness of the concepts.

(1) To reduce plate thickness by adopting 47 kgf/mm^2 HTSS in order to obtain greater toughness.

(2) To lay out the special toughness-oriented steel plates appropriately in the ship hull structure.

In the course of construction, initial weld defects that could induce brittle cracks were removed by carrying out thorough non-destructive inspections.

An application of 47 kgf/mm^2 HTSS is shown in **Fig. 6**. This is the hatch side coaming in the midship section of the hull, which is subject to the largest hull girder bending. Its increased strength naturally contributes to the weight reduction of the hull structure and to the lowered center of gravity especially through reducing the weight of the hull upper section, resulting in an increase in the number of containers carried.

3.3 Characteristics to stop brittle crack propagation

In the rare event that a brittle crack should occur, its propagation must be arrested. For this purpose, steel plates with high toughness are required and they must be outstanding in stopping brittle crack propagation (arrestability). In this regard, we implemented a propagation and arrest test for brittle cracks by using a large scale structural test model that was made to simulate the actual hull structure as closely as possible. The 8,000 tonf tensile tester and the structural test model which were used for the test are shown in **Fig. 7**. The test model used was the largest of its kind with a height of about 2.5 m and with a distance of 7.2 m between the load pins. In this large scale test, a defect as the fracture starting point was prepared on the upper part of the test hull and tensile loads equivalent to the design stress for the hull were applied in the longitudinal direction. At the same time, by keeping the temperature low and applying an impact load to the defect, brittle cracks were artificially started. These brittle cracks were propagated on the test steel plate, where the arrestability against brittle crack propagation was examined. **Figure 8** shows the test results on the shelf plate (cruciform joint) type, while **Fig. 9** shows the test results on the ultra wide duplex ESSO type subject to more severe conditions. By adopting the design concept described in Section 3.2, we confirmed that brittle cracks were arrested in both tests and verified that the ability to arrest brittle cracks was obtained as planned.

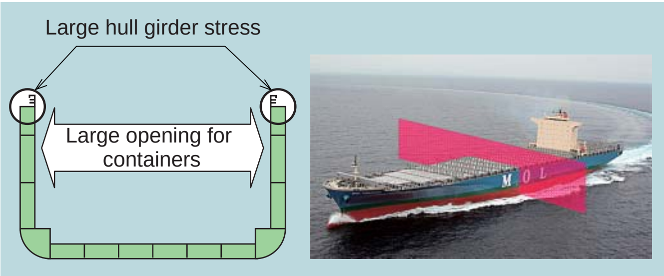


Fig. 5 Structural characteristics of container ship (midship section)

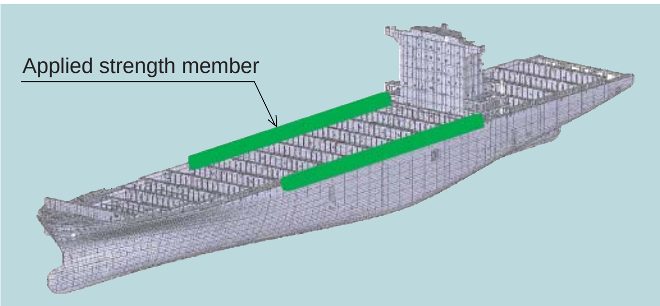


Fig. 6 Application of 47 kgf/mm^2 HTSS

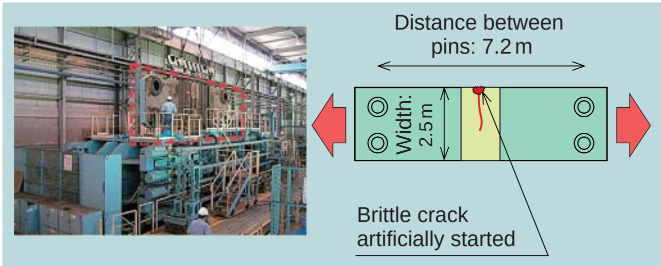


Fig. 7 Tester and test hull to measure resistance to large scale brittle crack propagation

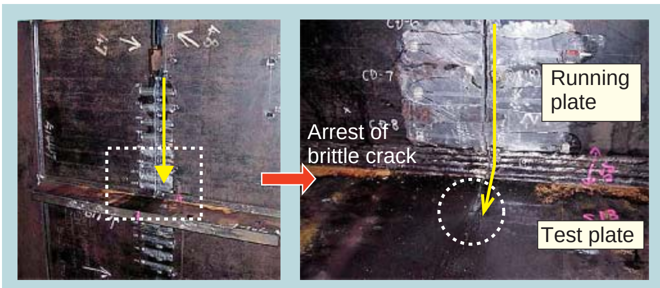


Fig. 8 Results of large scale brittle crack propagation arrest test (shelf plate)

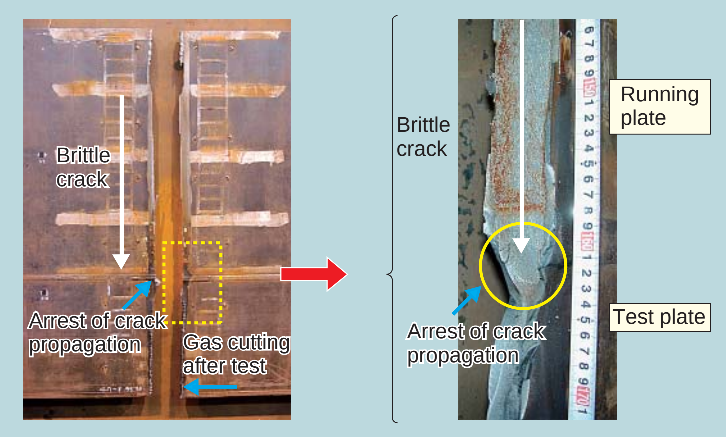


Fig. 9 Results of large scale brittle crack propagation arrest test (ultra wide duplex ESSO test)

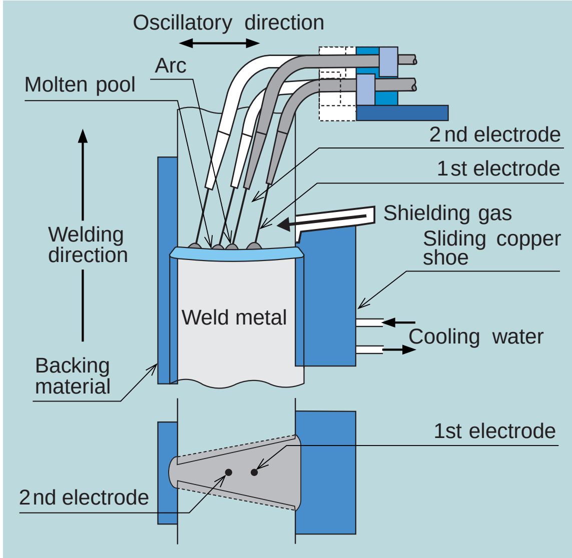


Fig. 10 Schematic drawing of tandem-electrode VEGA welding method

4. Welding

4.1 Welding process

The tandem-electrode VEGA (vibratory electro-gas arc welding) process was adopted for the vertical butt welding of the 47 kgf/mm^2 HTSS plate. The tandem-electrode VEGA welding process was developed jointly by Nippon Steel Welding Products & Engineering Co., Ltd. (the present Nippon Steel & Sumikin Welding Co., Ltd.), Nippon Steel Corp., and MHI. As shown in **Fig. 10**, this welding process uses two welding electrodes arranged in parallel to the plate which are automatically raised while being oscillated across the weld. A sliding copper shoe with a shielding gas supply port is mounted on the front face of the groove and there is a ceramic backing plate on the rear face of the groove. As this welding process obtained satisfactory results in the actual welding of 40 kgf/mm^2 HTSS with plate thickness of 65 mm or less, we adopted this welding process also for the 47 kgf/mm^2 HTSS.

As shown in **Fig. 11**, the tandem-electrode VEGA process welding speed is about twice that of the conventional single-electrode welding process and reduces the welding heat input to 85 to 90% of that of single-electrode welding. Because of these, improvements in welding efficiency and prevention of a drop in toughness of the weld heat-affected zone (HAZ) were attained. Also for the welding material, welding wire (EG-47T) that optimizes the matching of strength between the weld metal and the base metal, described in Section 4.2, was developed and used in the actual ship construction.

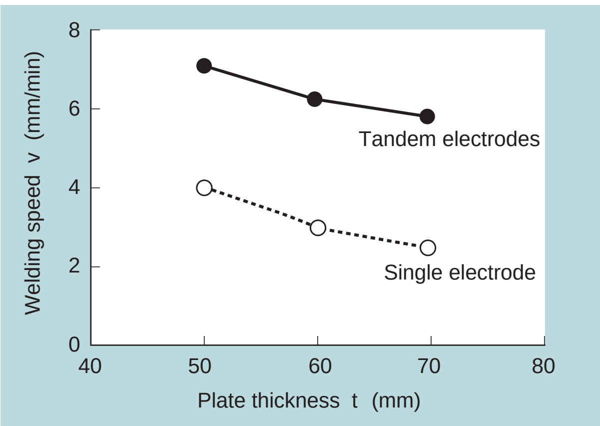


Fig. 11 Relation between welding speed and plate thickness

4.2 Welded section characteristic

The fracture toughness (Kc) of welded joints of extra-thick, high-strength steel plates is affected by the matching of strength (hardness) between weld metal and the base metal.

Figure 12 shows the relation between the experimental value result (Kc (–20°C)) taken from the center-notched wide-plate tensile test in which a notch is prepared on the fusion line of the welded joint (width 400 mm, notch length 240 mm, test temperature –20°C) and the Kc value at –20°C estimated from the results of a Charpy impact test of the fusion line section.

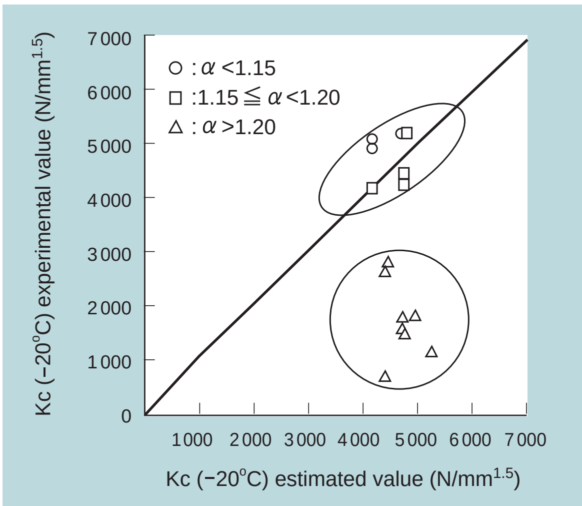


Fig. 12 Relation between matching of weld metal-to-base metal hardness and fracture toughness value

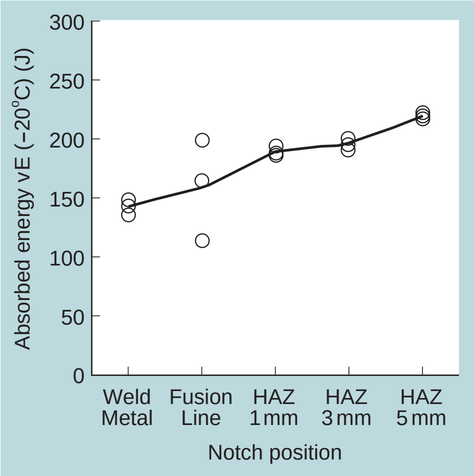


Fig. 13 Results of Chalpy impact test

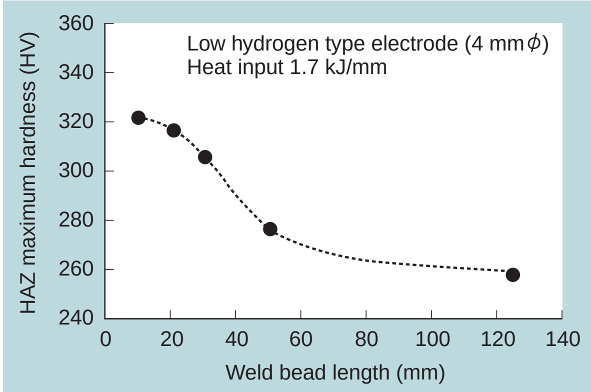


Fig. 14 Results of HAZ maximum hardness test

In Fig. 12, the data is classified based on the ratio (α = HV(WM)/HV(BM)) of the weld metal hardness (HV(WM)) and the base metal hardness (HV(BM)) of the welded joint to be tested. It was indicated that, in some data groups where α exceeded 1.2, the experimental values did not correspond to the estimated values (the experimental values are obviously lower than the estimated values.) This suggests a possibility that the fracture toughness may have been dropped in some cases even if the notch toughness levels expressed in the Charpy impact test are the same and, therefore, there is a danger of judging the toughness of welded joints of extra-thick, high-strength steel plates based on the results of the Charpy impact tests alone.

In order to ensure the quality of the welded joints matching the strength (hardness) between the welding metal and the base metal is essential, as described above. In consideration of the effect of strength matching on fracture toughness, we developed the tandem-electrode VEGA welding wire (EG-47T) which was mentioned in Section 4.1.

Figure 13 shows an example of the results of a 2 mm V-notch Charpy impact test of a 47 kg/mm^2 HTSS tandem-electrode VEGA welded joint using the newly developed wire (EG-47T). The mean value of the absorbed energy at −20°C (vE (−20°C)) is above 100 J in all the notch positions. It also indicates outstanding Charpy impact properties. Further, a center-notched wide-plate tensile test of the welded joint was conducted and sufficient fracture toughness was confirmed.

Figure 14 shows the results of a maximum hardness test (JISZ3101) in the heat-affected welding zone (HAZ) which was conducted to assess the cold cracking properties of HAZ. The results show that the HAZ maximum hardness of the 47 kg/mm^2 HTSS is below the hardness level (400 HV) defined by the JSQS[1] at which cold cracking is prevented, indicating it has sufficient capability to prevent cold cracking. This confirms that the cold cracking performance of 47 kg/mm^2 HTSS is equivalent or superior to that of the conventional shipbuilding steel plates and ensures sufficient reliability to prevent the occurrence of cold cracking defects during manufacturing.

5. Conclusion

MHI has developed the world's first 47 kg/mm^2 HTSS by responding to the trend toward larger container ships and used it on an actual ship. Its major characteristics are as follows.

(1) Through a combination of reduced thickness realized by increased strength and the improved toughness of the steel material, the brittle crack performance level has been increased and the reliability of the ship hull has been improved.

(2) Due to the reduced weight realized by the increased strength of the steel, cargo tonnage has been increased, thus contributing to the improvement of propulsive performance and fuel consumption.

(3) As described above, we have been able to supply a product which helps improve both safety and environmental friendliness by responding to our customers' needs.

The 47 kg/mm^2 HTSS is not just a high strength steel. It can both reduce the weight and improve the reliability of ship hulls when used in an appropriate design. This approach, we believe, will eventually become the global standard in the development and construction of mega container ships for the future.

Reference

(1) Japan Shipbuilding Quality Standard (JSQS) (1985)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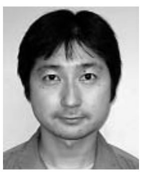
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