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Improvement in Safety of Ships by Use of Steel with High Crack Arrestability (HIAREST)

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Abstract

Ships are required to have safety and reliability standards high enough to minimize the loss of lives and the occurrence of marine contaminating accidents that could result from fractures in their hulls. A plate steel with extremely good crack arrestability, named designated HIAREST, was investigated for its effectiveness in enhancing the safety of ship hull structures. In such emergency situations such as when that a ship collides with another or runs aground, conventional steel plates are plastically damaged and are unable to arrest the propagation of any brittle cracks that may occur. The ability of the HIAREST to arrest the extension of brittle cracks when applied to the important hull members of ships was verified by experiments, including large-scale fracture tests. The Class-Notation system established by Nihon Kaiji Kyokai (Classification Society) to indicate the improved safety of ships built of HIAREST steel plates is also described.

1. Preface

Ship accidents are still far from being extinct and we continue being informed of cases such as marine pollution caused by collisions or groundings of very large crude oil carriers (VLCCs), casualties involved in sinking of overage ships, etc. The large-scale environmental damage caused by sea water pollution due to the sinking of the aged oil carrier Nakhodka in the Japan Sea a few years ago is still fresh in our memory. In this respect, construction of safer and more reliable ships for preventing casualties and environmental damages due to destruction of a ship's hull has been strongly required.

The double hull design of oil carriers is expected to reduce the danger of cargo oil spillage through prevention of the inner hull destruction at groundings and collisions of the vessels. Possibilities are pointed out, however, that the ship hull structure members near the collision point suffer a large plastic strain and the steel material's resistance against brittle fracture is significantly deteriorated, leading to secondary catastrophic destruction of the vessel triggered by brittle fractures initiated near the collision point. For preventing such a catastrophic propagation of destruction from happening, it is considered effective to use a steel material having a high capability to stop propagation of brittle fractures (crack-arresting capability) for strategically selected portions of the structure.

The present report describes characteristics of a new type of steel named "HIAREST (High crack Arrestability Endowed Steel)"[1-3] with ultra fine-grained surface layers developed for realizing a quantum improvement in the crack-arresting capability, as well as a study result[4,5] regarding integrity of structural steel materials for ship hull under emergency situation such as collisions and groundings, and also a new Class-Notation system[6] of safety of ships built using the steel with high crack-arresting performance.

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2. HIAREST (High Crack Arrestability Endowed Steel plate)

2.1 Characteristics of HIAREST

HIAREST is a hybrid type steel plate product of a structure wherein multiple layers are arranged in the thickness direction with surface layers having high anti-brittle fracture (crack-arresting) capability thanks to an ultra-fine crystal grain structure (1 - 3 μm), the finest in the world to be manufactured in an industrial scale. **Photo 1** shows macro- and microstructure in cross section of a HIAREST plate. The darker layers at the surfaces, about 1/6 of the plate thickness, are the surface ultra-fine crystal grain layers (hereinafter SUF layers/portions).

Chemical composition of the product is the same as the conventional steels, not containing any special elements for obtaining the multiple layers or the ultra-fine crystal grain structure. Hence, it enjoys as good weldability and workability as the conventional steels together with various advantages of the ultra fine grain structure.

2.2 Comparison of low temperature toughness between SUF layers and mid-thickness portion

Sub-size Charpy test pieces (3 mm thick) were cut out from the SUF portion and the mid-thickness portion, and their ductile-brittle transition behavior of fracture was tested. The results are shown in **Fig. 1**. It is clear from the figure that the SUF portion is far more resistant against brittle fracture than the mid-thickness portion.

2.3 Improved crack-arresting performance by formation of shear lips

One of the outstanding characteristics of HIAREST is its extremely high crack-arresting performance to stop the propagation and expansion of brittle fracture in comparison with the conventional steels. **Photo 2** shows a fractograph of a HIAREST plate tested by a temperature gradient-type ESSO test, a method specially designed for evaluating the crack-arresting performance. While the mid-thickness portion is fractured in a brittle manner, the SUF portion is fracture in a ductile manner resulting in a plastically deformed parts called "shear lips". The shear lip exerts a great amount of braking effect to propagation of brittle cracks and thus remarkably raises the crack-arresting capability of the plate[7]. **Fig. 2** shows a comparison of the crack-arresting capability between the HIAREST and the conventional steels. Here it is clarified that HIAREST possesses the excellent crack-arresting capability.

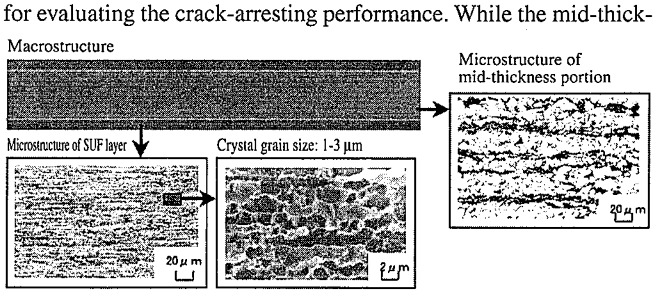


Photo 1 Macro- and microstructures of HIAREST

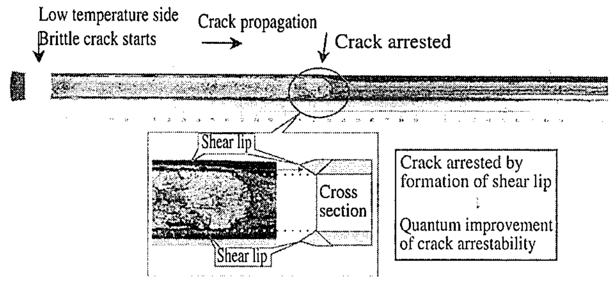


Photo 2 Characteristics of HIAREST fracture surface in ESSO test specimen

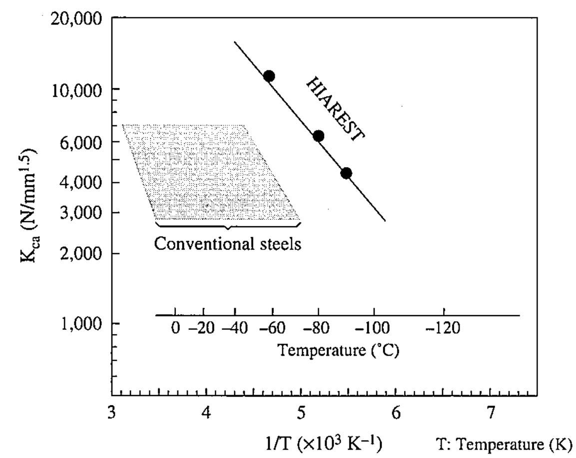


Fig. 2 Comparison of crack arrestability of HIAREST and conventional steels

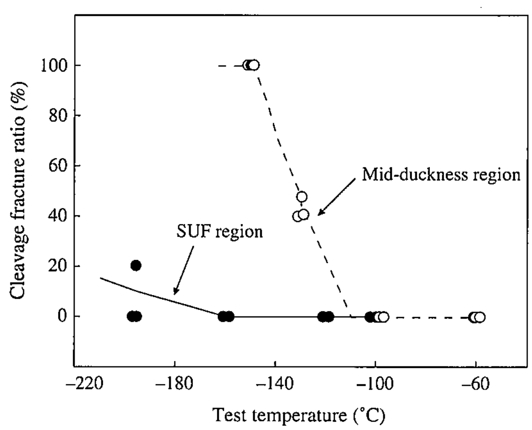


Fig. 1 Comparison of low temperature toughness of surface layer and mid-thickness regions of HIAREST

3. Study on Assessment of Ship's Safety

3.1 Philosophy regarding ship safety assessment

Generally speaking, ships are designed to have enough safety margins under normal operating conditions, but the same is not necessarily true under accident conditions such as collision and grounding. When steel members of ship's hull are damaged from collision or grounding, brittle fractures may take place. Brittle fractures propagate and expand in the damaged hull members and, in extreme cases, may lead to catastrophic and instantaneous destruction of the ship. In this respect, the authors conducted an analysis of level of damages inflicted on the ship hull steel members under a collision condition between two VLCCs and also an evaluation of crack-arresting capability of the steel materials after the damages.

3.2 Simulation of ship hull damage by collision[4,5]

Fig. 3 shows results of damage simulation of ship hull structure under a collision between two VLCCs obtained by the nonlinear FEM program LS-DYNA3D. The collided ship (300kDWT, double-hulled) is supposed to be fully loaded, while the colliding ship (280kDWT) in a ballasted condition hit the other in right angles at the center of a cargo tank. The penetrating distance of the colliding ship into the collided ship from time to time is shown in Fig. 3. The outer hull of the collided ship fractures at a penetration distance of 3.86 m and the inner hull begins to break at a penetration of 7.71 m.

Sheer strake is one of the most important members of the ship hull structure and the simulation shows that the plastic strain imposed thereon until the rupture of the inner hull is as high as 5 - 10%. Therefore, it is important to consider the influence of plastic strain induced in a steel plate on its properties for studying safety of ships under accident conditions.

3.3 Effects of plastic strain on crack-arresting performance

3.3.1 Results of standard ESSO test

A plate of HIAREST with thickness of 25 mm and another of KE36 steel (under the NK Standard instituted by Nippon Kaiji Kyokai, Class NK for short, a Japanese member of the International Association of Classification Societies) were used as test materials. Chemical compositions of the two steels are nearly identical. Some specimens of both the steels were given 5% and 10% of plastic strains by imposing tensile loads for comparison with others without plastic strain and'then all the specimens underwent 500 mm width temperature-gradient-type ESSO tests. **Fig. 4** shows brittle fracture arresting temperature and K_{ca} (critical stress intensity factor for arresting brittle fracture) of the test materials obtained from the tests. Crack-arresting performance was largely deteriorated by the plastic strain induced: whereas the temperature for K_{ca} = 4,000 N/mm$^{1.5}$ of the strain-free KE36 steel was –40°C, the same after a 10% plastic straining was fond to be as high as 0°C. Crack arresting capability of HIAREST

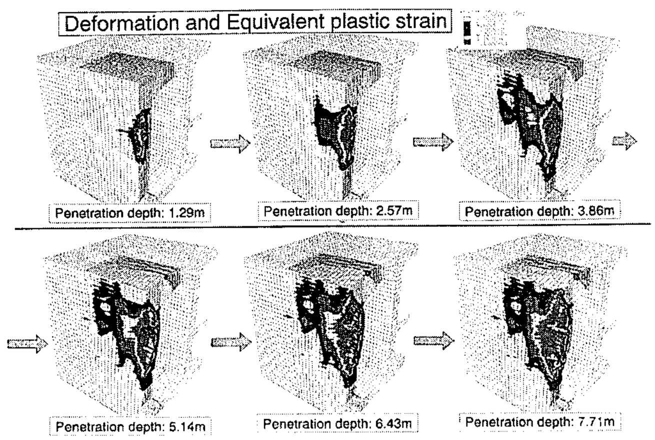


Fig. 3 Plastic strain distribution of collided ship at collision of two VLCCs[4)]

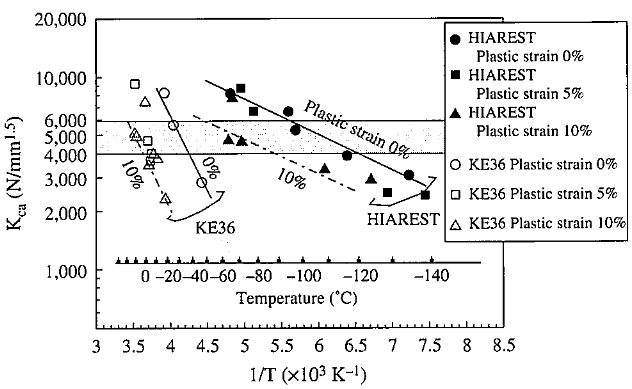
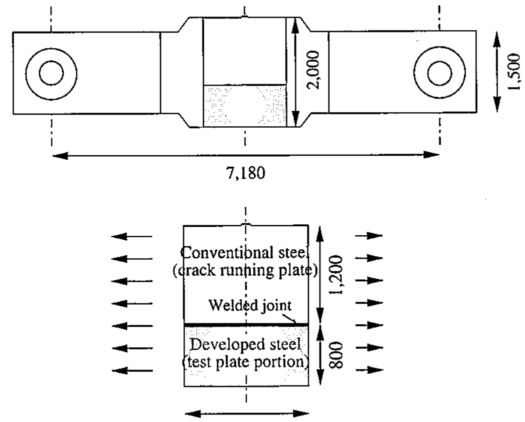
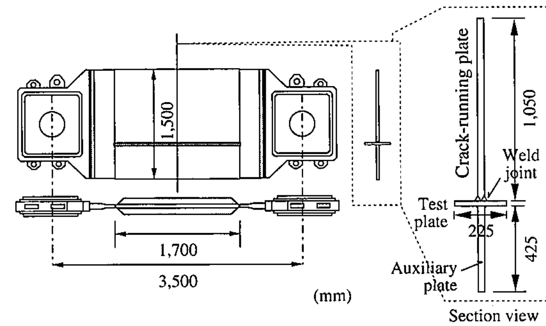


Fig. 4 Effects of plastic strain on crack-arrestability



(a) Specimen for ultra-wide duplex ESSO test



(b) Specimen for shear strake model test

Fig. 5 Large-scale fracture tests

was also worsened by pre-straining, but to a far smaller extent than KE36: its performance after pre-straining was yet better than that of the strain-free KE36, as observed in the figure.

3.3.2 Results of ultra-wide duplex ESSO test

Fig. 5 (a) shows a test piece for ultra-wide duplex ESSO test for simulating a part of actual ship hull structure. **Photo 3** shows an example of fractured test piece where KE36 steel was used in the crack propagation portion and HIAREST in the test plate portion. It can be observed that a brittle crack which propagated through the KE36 plate was arrested by forming shear lips in HIAREST when it reached the HIAREST plate.

Shear strake model tests (Fig. 5 (b)) were also conducted to simulate the fracture around shear strake. The results are shown in **Fig. 6**. The solid marks in the figure mean that the cracks were not arrested and the open marks mean that they were successfully arrested. The temperature ranges shaded dark in the figure show the areas where the K_{ca} value by the temperature-gradient-type ESSO test was 6,000 N/mm$^{1.5}$ or above and those shaded light show the areas where the same value was 4,000 - 6,000 N/mm$^{1.5}$. The KE36 steel plastically pre-strained by 10% failed to arrest brittle cracks in these large-scale fracture tests even at 0°C. This means that the conventional steels which meet the Grade E requirements in a strain-free condition can show having sufficient crack-arresting capability, but a poor performance under a pre-strained condition. In this respect HIAREST maintains sufficiently high crack-arresting capability even after a plastic strain is imposed, and thus it is expected to be capable of preventing propagation and extension of brittle cracks under accident conditions.

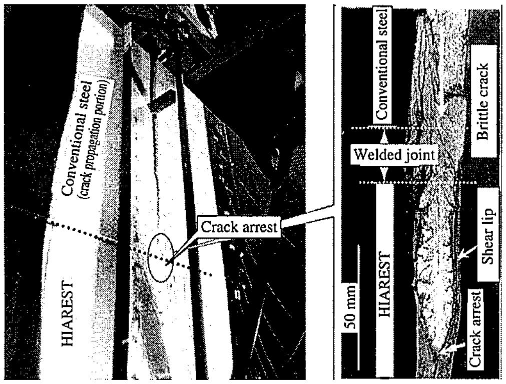


Photo 3 Verification of crack-arrestability of HIAREST by ultra-wide duplex ESSO test (–70 °C, arresting)

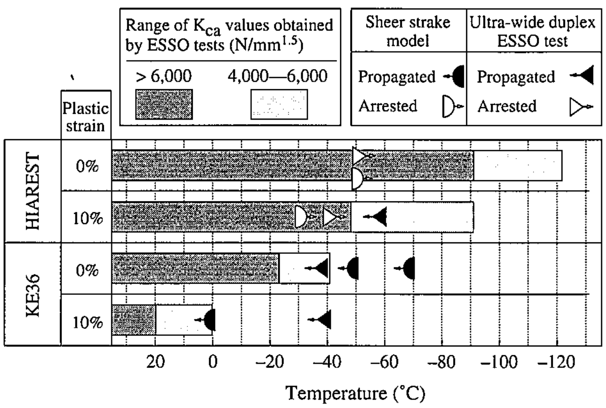


Fig. 6 Results of crack arrestability assessment by large-scale model fracture tests

4. Application of HIAREST to Ship Hull Structure

4.1 Safety enhancement philosophy by the use of HIAREST

It is highly probable that, under emergency situations such as collision or grounding of ships, catastrophic accident can occur if brittle fractures way initiate, because crack-arresting capability of the steel materials is significantly spoiled by the plastic strain induced by such accidents. By using a steel material capable of maintaining the crack-arresting capability even under pre-strained conditions for the strategically selected important components of the hull as shown in **Fig. 7**, however, it is expected that propagation and expansion of brittle fractures can be prevented.

4.2 Class-notation of Nippon Kaiji Kyokai (Class NK)[6)]

Nippon Kaiji Kyokai has acknowledged HIAREST and equivalent steels having sufficient crack-arresting capability ($K_{ca} \geq 6,000$ $N/mm^{1.5}$ at the design temperature) under a 10% plastic strain condition as "High Arrest Steel Plate" and instituted a new class-notation for recognizing safety of the ships in which the High Arrest Steel Plates are used for their key structural members. This is the first notation directly relating to the safety of ship among various notations widely applied in the maritime world, and American Bereau of Shipping (ABS) and other classification societies are preparing to establish similar notation systems.

Fig. 8 (a) shows examples of the Class-Notation indications and (b) shows the portions of ship hull where the new material is to be applied. The Notation system specifies whole cargo-part length, 0.6L at ship center, 0.4L at ship center, etc. (L = ship length) depending on

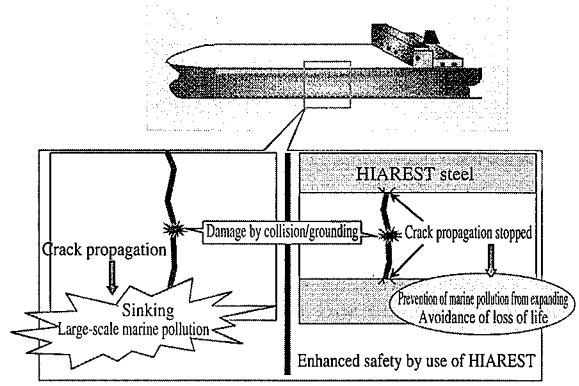
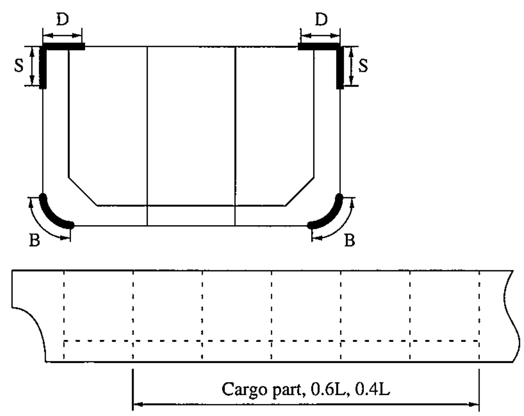


Fig. 7 Safety enhancement philosophy by the use of HIAREST

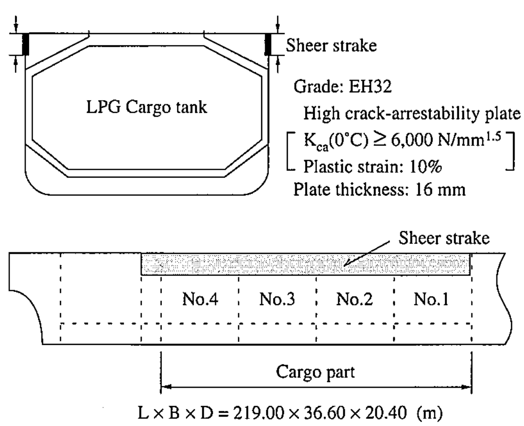
Class-Notation \ Hull structure	Hull members: Deck stringer (D)	Sheer strake (S)	Bilge strake (B)
H-ARST/D	○	—	—
H-ARST/S	—	○	—
H-ARST/B	—	—	○
H-ARST/D&S	○	○	—
H-ARST/D&B	○	—	○
H-ARST/S&B	—	○	○
H-ARST/D, S&B	○	○	○

○: HIAREST steel applied

(a) Examples of notation marks



(b) Hull members for application



(c) Example of application to LPG carriers

Fig. 8 Outline of NK Class Notation and its application example[6)]

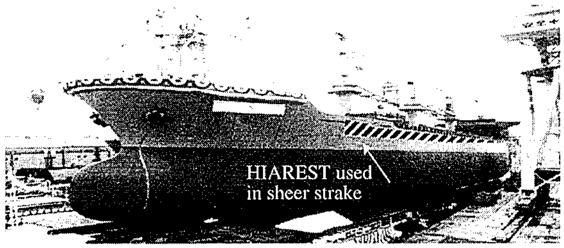


Photo 4 An example of HIAREST applied ship

the type of the ship. Fig. 8 (c) shows an application example of the high crack-arresting capability steel to an LPG (liquefied propane gas) carrier.

4.3 Example of actual application to ships

HIAREST has steadily accumulated records of actual applications to ship structures such as the first application to the LPG carrier in 1995, then a bulk carrier (See **Photo 4**) in 1996, a wood chip carrier and an iron ore carrier, etc. in 1997. 2,000 tons of HIAREST has already been commercially used for ships. Its applications to marine structures and repairs of aged ships for improving safety margins are also being considered.

5. Conclusion

Enhanced safety and reliability of ships are strongly required for the purpose of minimizing loss of life and ocean pollution caused by fracture of ship's hulls. In this respect, simulations of ship collision fracture and comparative evaluation of crack-arresting capabilities of steel materials were conducted for the purpose of assessing safety improvement effects of HIAREST with a remarkably high crack-arresting capability when applied to structural members of ship hulls. As the results, the following facts were confirmed:

(1) In a collision between two VLCCs, a plastic strain in the range of 5 - 10% may be imposed on the sheer strake before the inner hull of a double-hulled vessel is broken.

(2) Crack-arresting capability of steel material is significantly damaged when 10% or so of plastic strain is imposed, and no crack-arresting performance can be expected of even the Grade E class steels at 0°C when such a plastic strain is inflicted.

(3) The HIAREST can retain sufficiently high crack-arresting capability even after it is imposed of a 10% plastic strain.

Use of HIAREST for ship's key structural members is expected to prevent brittle fractures from propagating even in the cases of emergency like collisions or groundings. A new class-notation system was instituted by Class NK for acknowledging increased safety of the ships for which the developed steel is used in specified key structural components.

HIAREST is a new steel material for enhancing safety and reliability of structures in view of protection of global environment and prevention of loss of life, and its application to a wider variety of uses not limited to the shipbuilding is actively studied.

Acknowledgement

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