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Ultra-high Crack-arresting Steel Plate (HIAREST) with Super-refined Grains in Surface Layers

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Abstract:

To ensure the brittle fracture safety of large welded structures, the steel plates to be used in such welded structures are required to have the ability to arrest the propagation of brittle cracks (brittle crack arresting capability) on the supposition of the occurrence of brittle fractures. Noting the important role the development of shear lips play in the brittle crack propagation arrest mechanism, we developed a new type of steel plate that is provided with top and bottom surface layers of ultrafine microstructure by working the ferrite structure during thermal reoccurrence to facilitate the shear lip formation. Designated HIAREST, the new steel was confirmed to be more capable of arresting brittle cracks than conventionally processed steel plates by forming shear lips with greater certainty during the propagation of the brittle crack. In advance of the application of steel plates to hulls of ships and other welded structures, their fatigue resistance and field fabricability should be confirmed. HIAREST was confirmed to have such properties equivalent or superior to those of conventional steel plates.

1. Introduction

It is extremely important to assure safety with respect to the brittle fracture of large welded structures. For ships[1,2] and low-temperature storage tanks[3,4], among others, the ability of welded structural steels to arrest the propagation of brittle cracks has been studied on the supposition of the occurrence of brittle fractures. This brittle crack arresting capability is practically applied as a double-integrity design concept[5] in some components. The appearance of steels with excellent crack arresting performance is expected to introduce the new safety design concept of preventing the extension of any brittle fractures that may occur to the fields of buildings, bridges, offshore structures, and other applications.

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Noting the important role played by shear lip formation (discussed in detail in section 3.1) in the brittle crack propagation arresting mechanism[6,7], we developed a new steel plate with an ultrafine microstructure in the top and bottom surface layers (designated HIAREST for high crack-arrestability endowed steel)[8-10] by applying the new metallurgical principle[11,12] of refining the grain size of the ferrite structure to a very small level by working during thermal reoccurrence.

2. Characteristics of HIAREST

2.1 Basic properties

HIAREST plates, having the chemical composition given in **Table 1**, measuring 18 and 25 mm in thickness, and equivalent to Grade EH36, were manufactured by introducing into an actual production line the new metallurgical principle[11,12] by which the ferrite structure can be very finely refined by working on heating. The tensile test results of the full-thickness plates are listed in **Table 2**. The cross-sectional macrostructures of the 18- and 25-mm thick HIAREST plate specimens are shown in **Figs. 1**(a) and **1**(b), respectively. The microstructures of the surface layer and mid-thickness portion of the 25-mm thick HIAREST plate are shown in **Figs. 1**(c) and **1**(d), respectively. The grain size of the surface layer is so small that it is difficult to recognize by optical microscopy. (This surface layer with ultrafine-grained microstructure is abbreviated to SUF). The SEM microstructure of the SUF is shown in **Fig. 2**(a). Assuming the grain to be circular, the average grain size is found to be 2 μm or less. As an example of the through-thickness grain size distribution of HIAREST, the average circle equivalent grain size determined by position in the thickness direction is shown in **Fig. 2**(b). The grain size is almost uniform in the SUF and abrupt change occurs at the boundary between the SUF and the rest of the plate. The transition region of the grain size was hardly observed at the boundary.

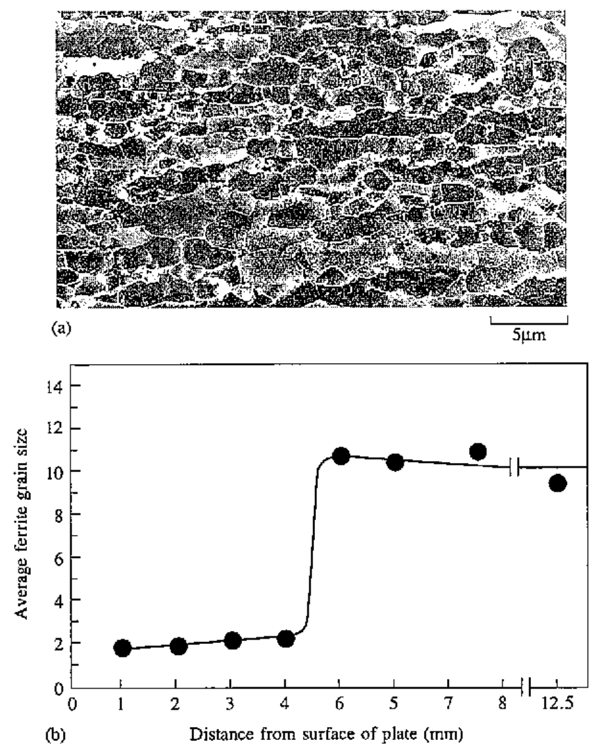


Fig. 2 SEM microstructure of SUF portion

Table 1 Typical chemical composition of HIAREST (mass%)

C	Si	Mn	P	S	Ceq
0.13	0.20	1.27	0.007	0.002	0.34

Table 2 Typical tensile properties of HIAREST (full-thickness specimens)

Thickness	Yield point	Tensile strength	Elogation
18mm	451MPa	503MPa	18%
25mm	431MPa	526MPa	23%

Specimen size: 200 mm GL × 25 mm width

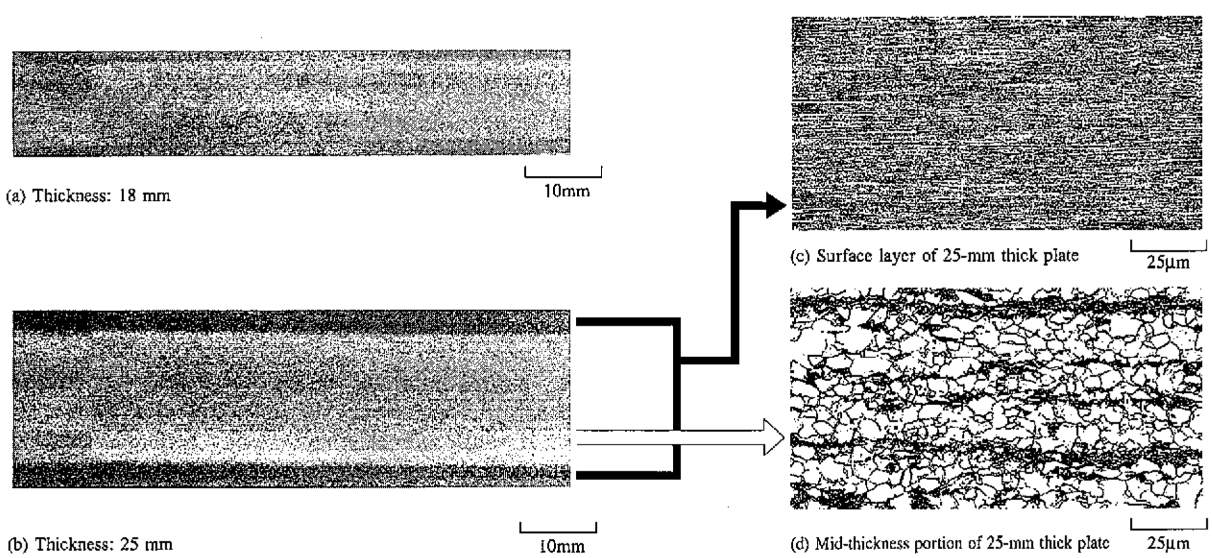
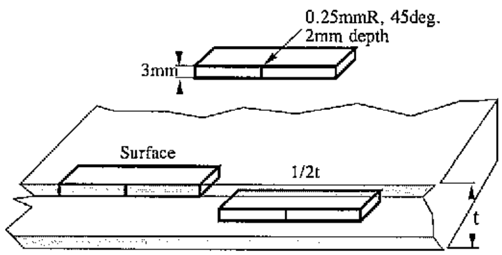


Fig. 1 Macrostructures of HIAREST (a) and (b), microstructure of surface layer of 25-mm thick plate (c), and microstructure of mid-thickness portion of 25-mm thick plate (d)

Table 3 Tensile properties of SUF and inner portions

	Position	Yield point	Tensile strength	Elogation
HIAREST	SUF	536MPa	577MPa	28%
	1/2t	450MPa	548MPa	27%

Specimen size: 30 mm GL × 12.5 mm width × 2.5 mm thickness



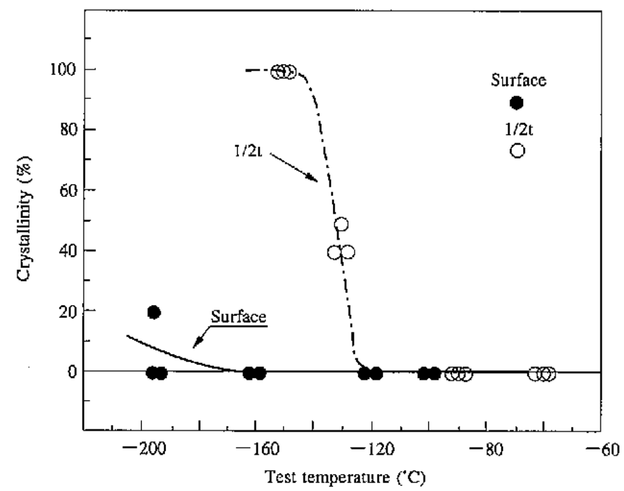


Fig. 3 Charpy impact properties of SUF (surface) and mid-thickness (1/2 t) portions

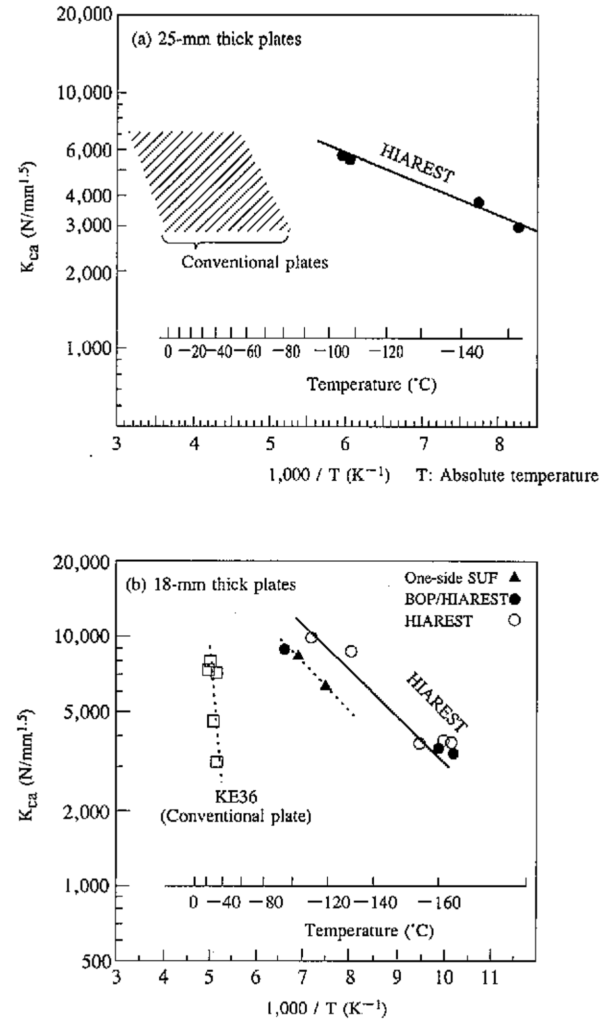


Fig. 4 ESSO test results of 25-mm thick HIAREST plates (a) and 18-mm thick HIAREST plates (b)

2.2 Mechanical properties of SUF

Tensile test specimens and subsize Charpy V-notch impact test specimens were taken from the SUF of a 25-mm thick HIAREST steel plate and tested. The mechanical properties of the SUF specimens were compared with those of mid-thickness (1/2 t) specimens.

The results of the tensile test of the SUF and mid-thickness specimens of HIAREST are shown in **Table 3**. The SUF portion is more finely grained than the mid-thickness portion, so that its yield point and tensile strength are higher. The subsize Charpy V-notch impact test results are shown in **Fig. 3**. Considering the fracture transition temperature of the 1/2 t portion is relatively low since the thickness of the specimen used is a small 3 mm. However, the transition temperature of the SUF portion is much lower and under -196°C. These results show that the SUF portion is higher in strength than the mid-thickness portion and features extremely good brittle fracture resistance as compared with the mid-thickness portion.

3. Brittle Crack Propagation Arresting Performance of HIAREST

3.1 Crack arrest toughness (brittle crack propagation arresting toughness), K_{ca}

The results of the temperature-gradient ESSO test on HIAREST are shown in **Fig. 4**. (This test is a standard testing method for evaluating the crack arresting capability of steel plates). At the same test temperature, HIAREST exhibits a higher K_{ca} value than steel plates of the same chemical composition produced by the conventional process, including TMCP (Thermo-mechanical controlled process). The temperature at which it achieves a K_{ca} value of 6,000 $N/mm^{1.5}$ is much lower than for the conventional plates.

The fracture of an ESSO test specimen of HIAREST is shown in **Fig. 5**(a). The development of shear lips was observed on the fracture surface of the SUF portion of HIAREST. Shear lips were formed even in the portions where the crack propagated at about -120°C. The through-thickness section of the fracture was etched in nital and the fracture was observed simultaneously with the microstructure. The results are shown in **Fig. 5**(b). It is confirmed that the shear lip portion corresponds to the SUF portion. **Fig. 6**

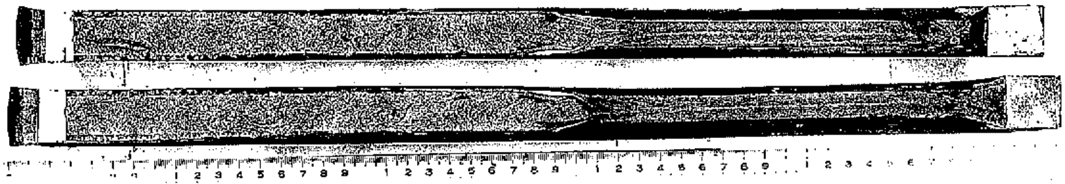


Fig. 5(a) Fracture and cross section of 25-mm thick HIAREST plate

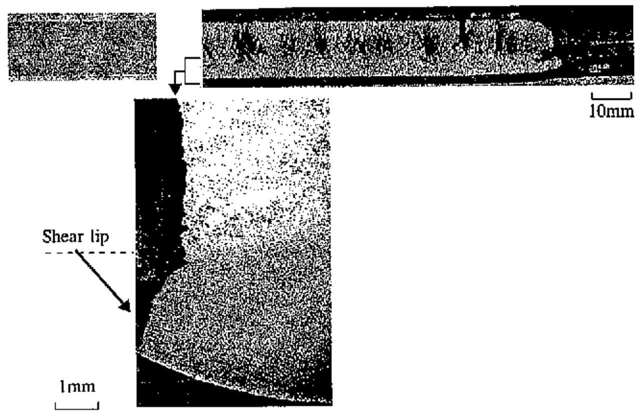


Fig. 5(b) Fracture and cross section of 18-mm thick HIAREST plate

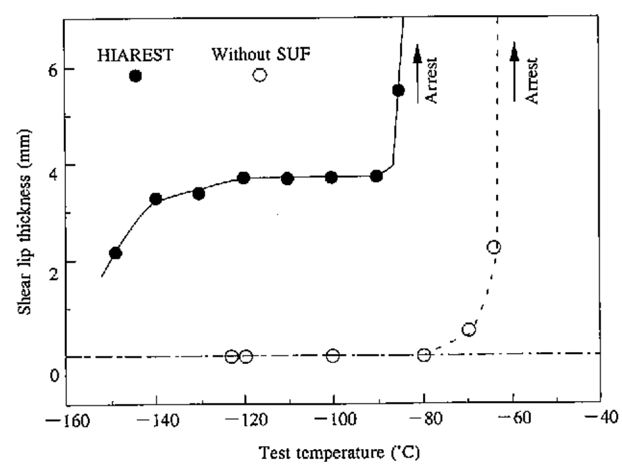


Fig. 6 Shear lip formation process in ESSO test specimens (25-mm thick)

shows the effect of the test temperature on the shear lip thickness (average for both the top and bottom surface layers) in the ESSO test specimen portions where cracks propagated. The ductile-brittle transition temperature of the SUF portion is lower by more than 80°C than that of the mid-thickness portion. The development of shear lips is observed immediately after the initiation of crack propagation.

3.2 Effect of shear lips in improving crack arresting performance

3.2.1 K_{ca} comparison between specimens with SUF and without SUF by grinding off

To confirm experimentally the effect of shear lips developed in the SUF portion in improving the crack arresting performance of HIAREST, specimens containing the internal structure alone were prepared by grinding off the top and bottom SUF portions of HIAREST and were then temperature-gradient ESSO tested. The K_{ca} values of the SUF-removed specimens are calculated by using the plate thickness compensation equation of WES to consider the thickness effect of K_{ca} from grinded thickness to the original thickness and are plotted by open circles in **Figs. 7**(a) and **7**(b).

3.2.2 K_{ca} improvement quantification by Kraft model

The effect of shear lips in improving the K_{ca} value can be explained[9,10] by using the Kraft model[13]. The Kraft model for K_{ca} improvement is described in **Fig. 8**. The plastic work rate of the shear lip region is thought to change with the temperature at which the shear lip is formed. Here it is assumed to be 200 MPa·mm[14], irrespective of the temperature. The ESSO test (crack arrest evaluation test) results of 18-mm HIAREST plate specimens with the SUF retained on both sides (with SUF), with the SUF removed on one side (with one-side SUF), and with the SUF removed on both sides (without SUF) are plotted in **Fig. 7**(b). The presumed K_{ca} values of HIAREST calculated by adding to the K_{ca} value of the specimens with SUF the effect of shear lips in improving the K_{ca} value as estimated by the Kraft model are indicated by the dot-dash line. The presumed K_{ca} values of the specimens with one-side SUF are

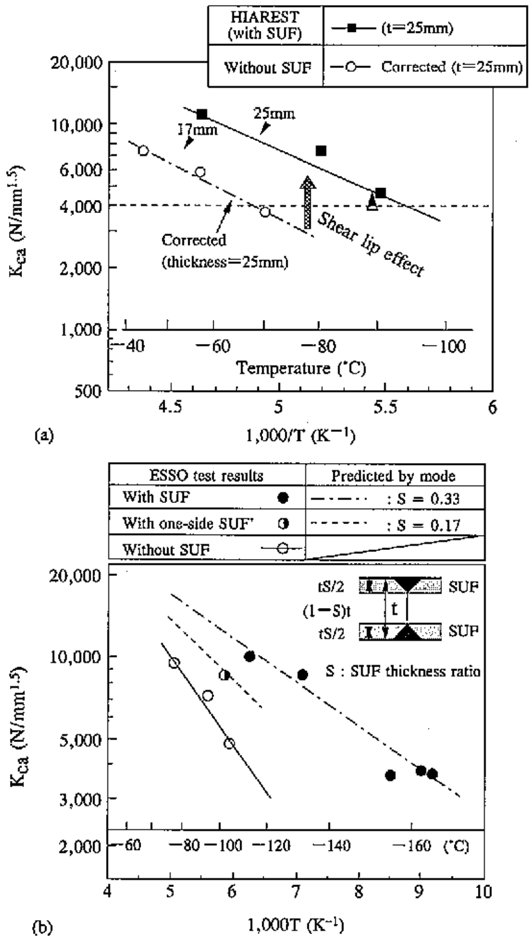


Fig. 7 K_{ca} data comparison of HIAREST specimens (25 mm-thick) with SUF and without SUF by grinding off

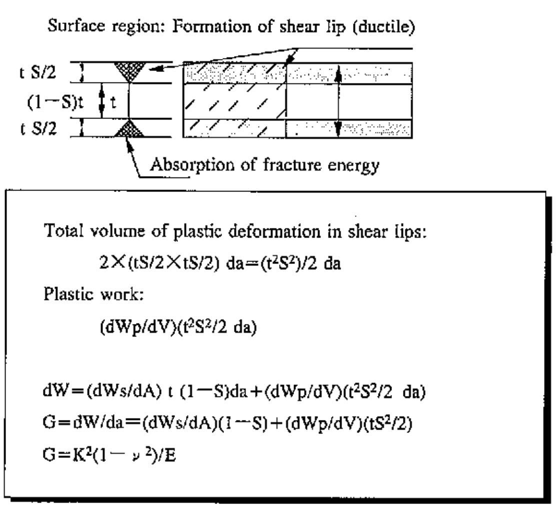


Fig. 8 Kraft model

indicated by the dotted line. The effect of shear lips in the SUF region can be explained fairly well by these rough approximations.

This suggests that the improvement in the K_{ca} value can be presumed from the SUF thickness and that when the SUF thickness is predicted to decrease, as for example in a corrosive environment, HIAREST can be selected to provide the necessary crack arresting capability by compensating for the predicted loss of the SUF thickness in the material stage.

3.3 Verification of long crack arresting performance by large fracture test

3.3.1 Ultra-wide duplex ESSO test (Type I)

The ultrawide-plate duplex ESSO test illustrated in **Fig. 9** was conducted by assuming the initiation of a brittle crack in the side plating of a ship colliding with another ship in an accident and by modeling the propagation and penetration of the crack into the sheer strake (the upper side hull plating) of the ship. In the ultra-wide duplex ESSO test, a test plate larger than a standard temperature-gradient ESSO test specimen and a crack-running plate are welded to form a large specimen. A brittle crack is initiated and propagated through the crack-running plate, and is introduced into the test plate. Whether or not the crack can be arrested (go or no-go) in the test plate is judged. The applied stress was 355 MPa (nominal yield strength) and equivalent to the stress at which steel deformation starts. The ability of HIAREST to arrest long cracks was evaluated at the temperature of −70°C judging whether or not the test plate could arrest the brittle crack.

For the purpose of comparison, the conventional steel plate KE36 was tested at the same tensile stress of 355 MPa and target temperature of −50°C. The results are shown in **Table 4**. While the conventional steel plate KE36 was not able to arrest the brittle crack, HIAREST was able to arrest the brittle crack. **Fig. 10**

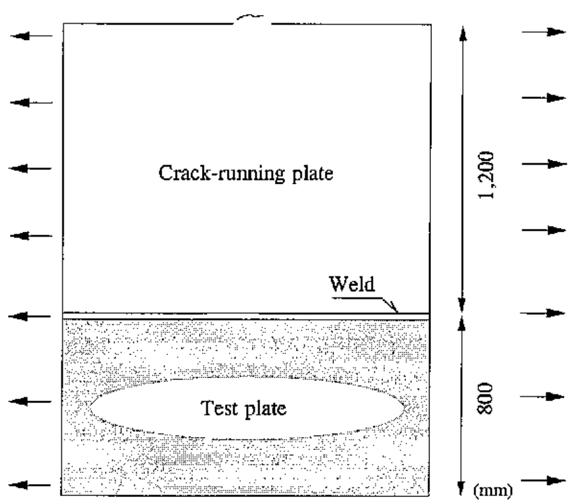


Fig. 9 Type I ultrawide-plate duplex ESSO test specimen

Table 4 Results of Type I ultra-wide duplex ESSO test

Test plate	Tset temperature	Result
HIAREST	-53°C	Arrest
EH36	-52°C	Go

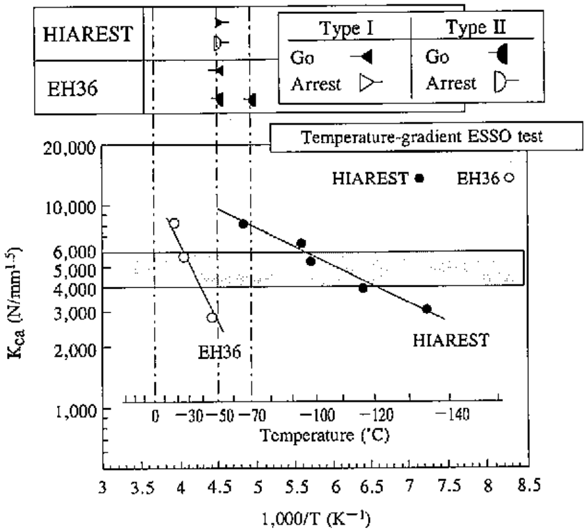


Fig. 10 Results of Type I and II ultra-wide duplex ESSO tests

shows the results of the ultra-wide duplex ESSO test (Type I) at the same test temperatures as those of the temperature-gradient ESSO test. The difference in the K_{ca} value between the two steels at about -50°C is large and attests to the superior crack arresting performance of HIAREST. An example fractograph from the ultra-wide duplex ESSO test (Type I) is shown in **Fig. 11**. A conspicuous shear lip is formed in the HIAREST (SUF) side of the butt weld with the crack-running plate (embrittled plate). The brittle crack is arrested in the HIAREST test plate.

3.3.2 Ultra-wide duplex ESSO test (Type II)

Another phenomenon expected to occur is that a brittle crack initiates in the upper deck of a ship and propagates into the sheer strake. Since its surface layers have an ultrafine-grained microstructure, HIAREST is assumed to have greater resistance to a brittle crack penetrating from the plate surface than to a through-thickness crack. A structure test was conducted by modeling the phenomenon in which a brittle crack originates in the deck, propagates, and penetrates into the sheer strake. The geometry of an ultra-wide duplex ESSO test specimen (Type II) is shown in **Fig. 12**. The crack-running plate and test plate were welded with complete penetration at right angles to each other. The auxiliary plate was fillet welded below the test plate to ensure a uniform stress distribution in the crack-running plate and test plate. Since the actual sheer strake has no such auxiliary plate, the test plate is to be evaluated as having an insufficient crack arresting capability if a brittle crack penetrates through the test plate and even if is arrested in the auxiliary plate.

The results of the ultra-wide duplex ESSO test (Type II) are summarized in **Fig. 10** and **Table 5**. **Fig. 13** shows fractures, each of which was obtained when a brittle crack was caused to penetrate into the test plate at -50°C. When the brittle crack propagating through the weld between the crack-running plate and the KE36 test plate penetrated into the KE36 test plate, it fractured the KE36 test plate. HIAREST arrested the brittle crack as soon as it penetrated into the surface layer.

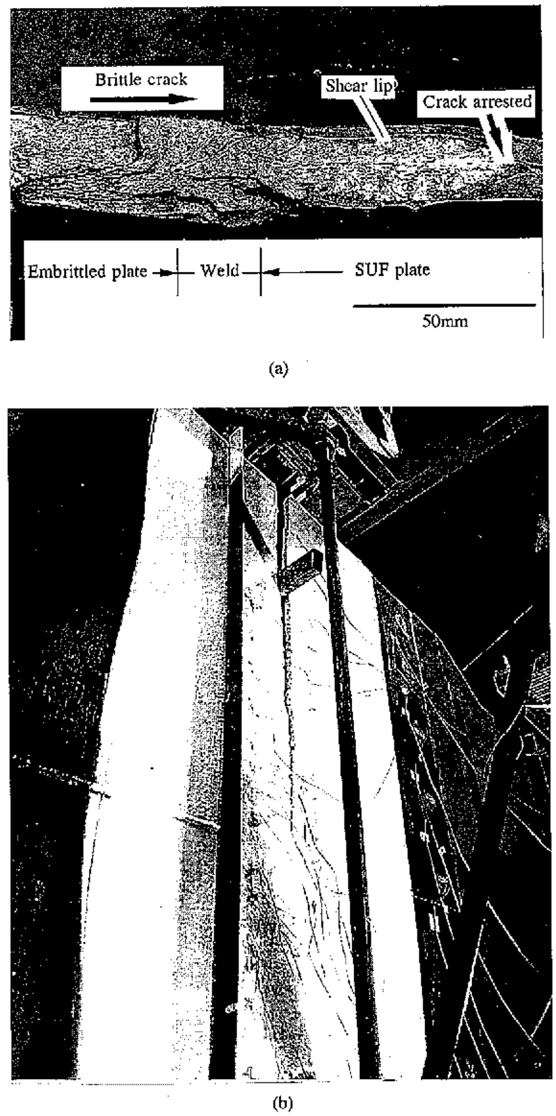


Fig. 11 Fracture of Type I ultra-wide duplex ESSO test specimen

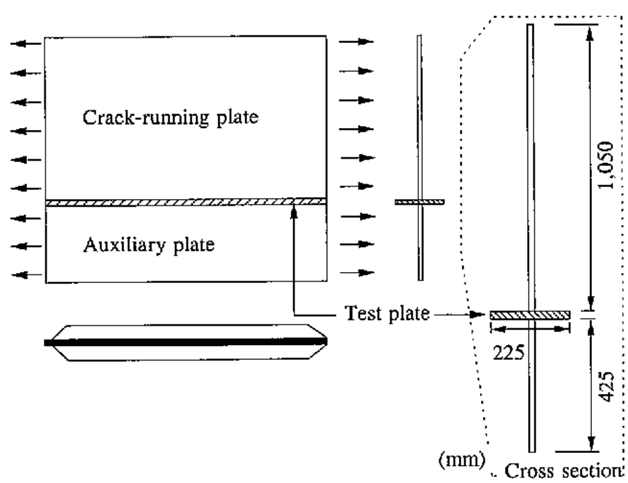
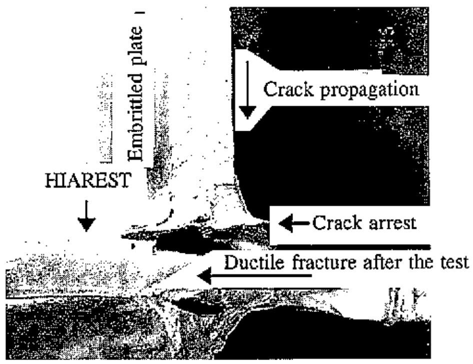


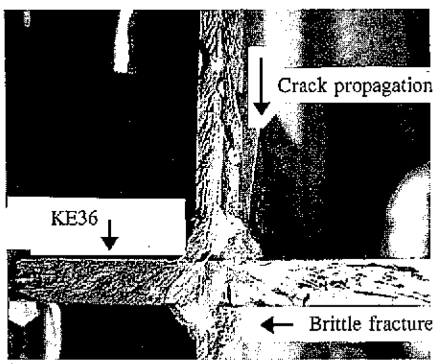
Fig. 12 Type II ultra-wide duplex ESSO test specimen

Table 5 Results of Type II ultra-wide duplex ESSO test

Test plate	Tset temperature	Result
HIAREST	-50°C	Arrest
EH36	-50°C	Go



(a) HIAREST (virgin) tested at -50°C



(b) KE36 (virgin) tested at -50°C

Fig. 13 Fractures of Type II ultra-wide duplex ESSO test specimens

3.4 Brittle crack propagation arresting performance of steels subjected to plastic strain

3.4.1 Significance of evaluating properties of steels subjected to plastic strain

When applied to the most important parts of the hull structure of a ship, such as the sheer strake, HIAREST is expected to exploit its excellent crack arresting performance in marine accidents, such as collidings or groundings. The results of analysis simulating collisions of very large crude-oil carriers (VLCCs)[15] indicate the possibility of a collision in the sheer strake region imposing plastic strains of about 5 to 10%. A large earthquake of the same magnitude as that of the Great Hanshin Earthquake of January 17, 1995 in western Japan is considered to subject structures to plastic strains as they badly deform. HIAREST and KE36 were studied for their crack arresting performance when subjected to plastic strains of about 5 and 10%.

3.4.2 K_{ca} characteristics of steels subjected to plastic strains

Test steel plates were subjected to plastic strains of about 5 and 10% by tensioning. The standard ESSO test results of the plates subjected to the plastic strains of 5 and 10% are shown in **Fig. 14** as compared with those of plates not subjected to the plastic strains. The plastic strain of 10% increased the crack arresting performance of both KE36 and HIAREST by about 30°C. The temperature at which the K_{ca} value reaches 6,000 N/mm$^{1.5}$ is -50°C for HIAREST and about +15°C for KE36. The K_{ca} value of HIAREST subjected to the plastic strain of 10% is sufficiently higher than that of KE36 not subjected to the plastic strain.

3.4.3 Large fracture test results of steels subjected to plastic strains

The results of the Type I ultra-wide duplex ESSO test conducted on steel plates subjected to the plastic strain of 10% at -40°C are shown in the upper part of **Fig. 14** and in **Table 6**. KE36 was failed to arrest long cracks, while HIAREST was succeeded to arrest long cracks. This proved that HIAREST has a sufficient crack arresting capability when subjected to the plastic strain of 10%.

When KE36 subjected to the plastic strain of 10% was tested at 0°C using Type II ultra-wide duplex ESSO test, the brittle crack could not be arrested in the test plate and led to the complete fracture of the specimen. When HIAREST subjected to the plastic strain of 10% was tested at -30°C in Type II ultra-wide duplex ESSO test, it was confirmed to be able to arrest the brittle crack. The fractures of these specimens are shown in **Fig. 15**.

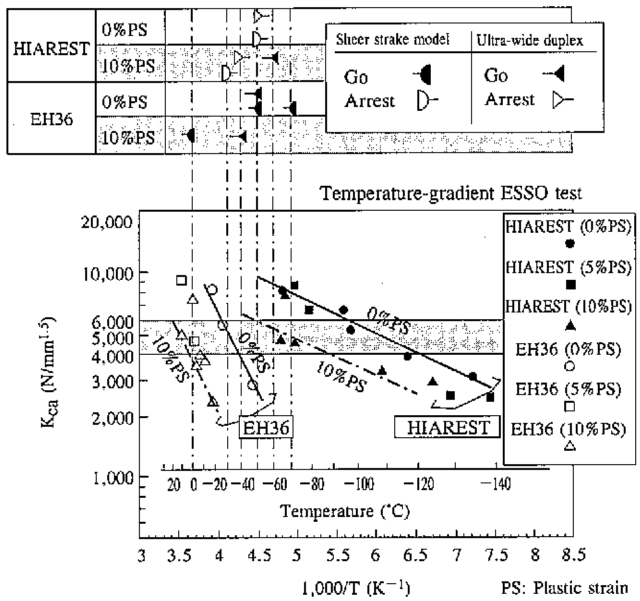
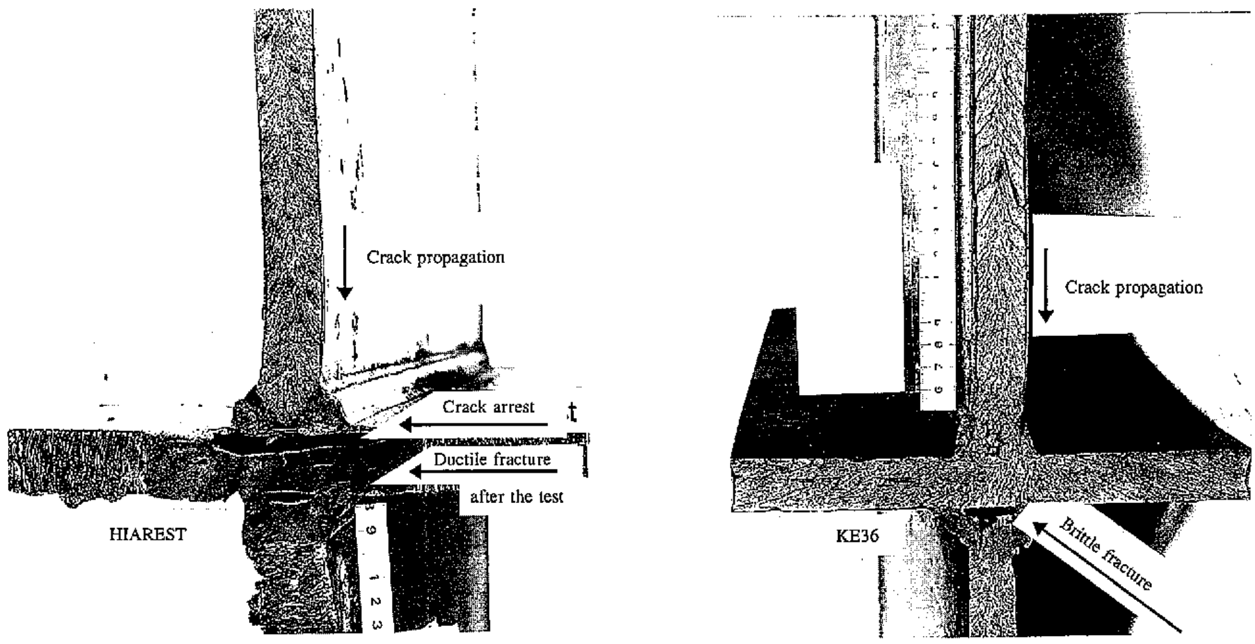


Fig. 14 Standard ESSO test and ultra-wide duplex ESSO test results of specimens subjected to plastic strain

Table 6 Ultra-wide duplex ESSO test results of specimens subjected to plastic strain

Method	Test plate	PS	Test temperature	Results
Type I	HIAREST	10%	-42°C	Arrest
		10%	-60°C	Go
	EH36	10%	-40°C	Go
Type II	HIAREST	10%	-30°C	Arrest
	EH36	10%	0°C	Go



(a) HIAREST (subjected to plastic strain of 10%) tested at -30°C   (b) EH36 (subjected to plastic strain of 10%) tested at 0°C

Fig. 15 Fractures of Type II ultra-wide duplex ESSO test specimens subjected to plastic strain

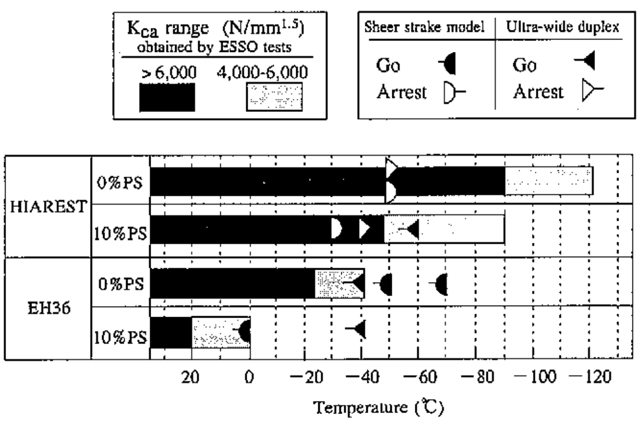


Fig. 16 Effect of 10% plastic strain on K_{ca} value of HIAREST and EH36 steel plates

3.5 Summary

The temperature regions where the 25-mm thick HIAREST and KE36 steel plates can maintain their crack arresting performance are shown in **Fig. 16**. The temperature region where the K_{ca} value of the specimens obtained by the temperature-gradient ESSO test is not less than 6,000 $N/mm^{1.5}$ is shaded dark. The temperature region where the K_{ca} of the specimens obtained by the temperature-gradient ESSO test is 4,000 to 6,000 $N/mm^{1.5}$ is shaded light. The ultra-wide duplex ESSO test results are denoted by marks indicating "go (crack propagated)" and "arrest (crack arrested)" for specific test temperatures.

According to these results, HIAREST is considered to be able to arrest brittle cracks in the ultra-wide duplex ESSO test and the sheer strake model test in the temperature region where it exhibits a K_{ca} value of not less than 6,000 $N/mm^{1.5}$. In the temperature region where it exhibits a K_{ca} value of not less than 6,000 $N/mm^{1.5}$ in the standard temperature-gradient ESSO test, HIAREST is thought to be fully capable of arresting long cracks under an applied stress equivalent to its nominal yield stress.

The temperature at which conventional EH36 exhibits a K_{ca} value of 6,000 $N/mm^{1.5}$ in the plastic strain-free condition is about -10°C. This means that EH36 has a practically sufficient crack arresting capability at the ordinary ship design temperature of 0°C. When EH36 is subjected to the plastic strain of 10%, however, its 0°C crack arresting performance can no longer be expected. When subjected to the plastic strain of 10%, HIAREST can still arrest long cracks at -40°C. This means that HIAREST can be expected to be fully able to arrest long cracks when applied to ships operating in seas at the lowest temperature of 0°C.

4. Brittle Fracture Resistance of Welded Joints

HIAREST is a steel plate that is markedly improved in crack arresting performance by shear lip formation during brittle crack propagation. When applying HIAREST to welded structures, it is important to know the fracture initiation characteristics of welds governed by the microstructure of the heat-affected zone (HAZ) that in turn is basically governed by the chemical composition of the steel. A study was made of the toughness and brittle crack initiation toughness of welded joints made with large heat input in steel plates of chemical composition suited for shipbuilding applications. The brittle crack propagation resistance of the welded joints was also investigated by large scale structure testing.

4.1 Toughness of welded joints

A cross-sectional macrostructure of a HIAREST welded joint is shown in **Fig. 17**. The ultrafine structure at the fusion line (boundary between the weld metal and the base metal) is eliminated under the influence of welding heat, and a normal HAZ structure is developed instead.

The Charpy V-notch impact test results of welded joints of this type are shown in **Fig. 18**. The results of center-notched wide tensile test (a test method designed to evaluate brittle fracture resistance) are shown in **Fig. 19**. HIAREST having the same chemical composition as Grade E shipbuilding steels was confirmed to possess welded joint toughness sufficient to meet specifications for shipbuilding steel plates.

4.2 Brittle crack propagation in welded joints

4.2.1 Brittle crack propagation in butt joints

Using one-side, single-layer, large-heat input welded joints (FCB joints) shown in **Fig. 17**, a brittle crack was initiated in the weld bond zone by an impact load through a wedge. The propagation path of the brittle crack was investigated by the large joint propagation test illustrated in **Fig. 20**.

The temperature distribution and crack propagation path of welded-joint brittle crack propagation test specimens are schematically shown in **Fig. 21**. The crack propagated along the bond (the boundary between base plate and weld metal) in the region near the crack initiation site where the specimen was cooled to a lower temperature than the test temperature. Before it reached the region at the test temperature of 0°C, the crack diverted into the base metal and was immediately arrested.

The fracture and appearance of a specimen near the brittle crack arrested point is shown in **Fig. 22**. After the test, the specimen was cross-sectionally machined to observe the crack propagation region, and the positional relationship between the crack propagation path and the welded joint was examined. The results are shown in **Fig. 23**. It is evident that when the crack diverted into the base metal, a shear lip immediately formed to arrest the crack.

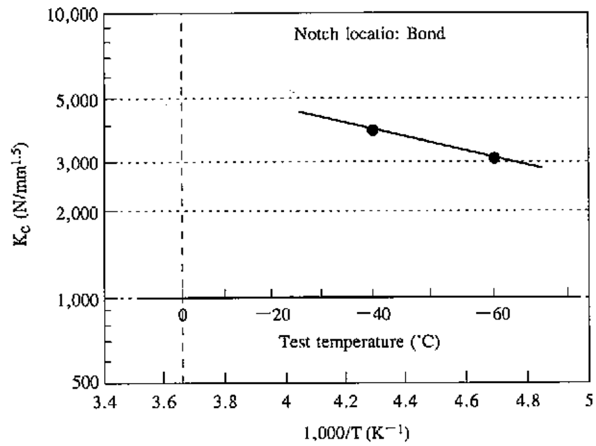


Fig. 19 Deep-notch test results of FCB welded joints

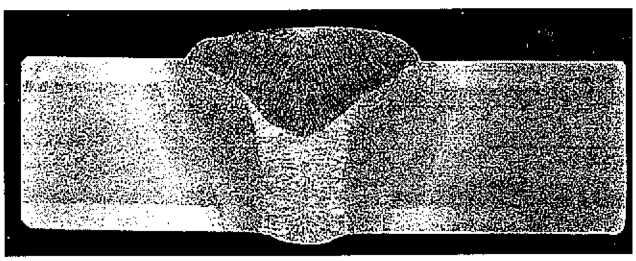


Fig. 17 Macrograph of FCB joint

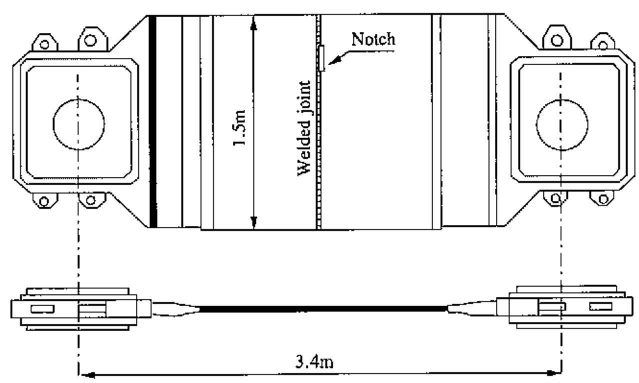


Fig. 20 Brittle crack propagation test method for welded joints

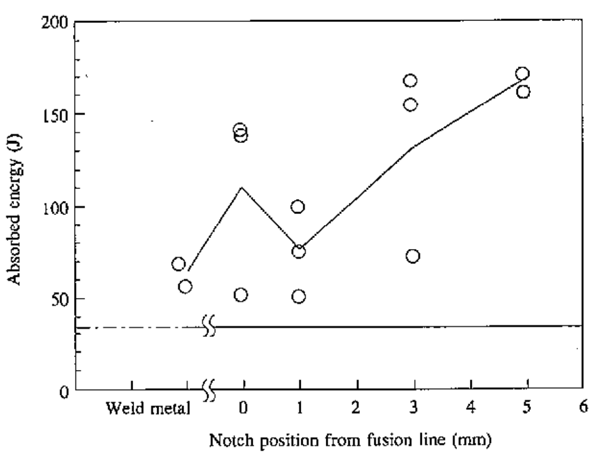


Fig. 18 Charpy test results of FCB joints

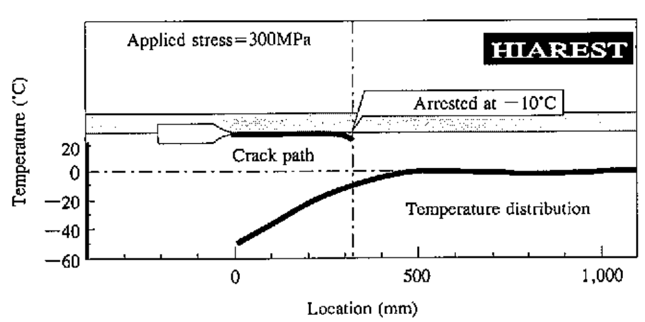


Fig. 21 Brittle crack propagation test results of plastic strain-free welded joint

The effects of the toughness ratio of the most embrittled zone to the base metal in the welded joints and the applied stress on crack propagation behavior in the welded joint are shown in **Fig. 24**. Former information (data obtained by the SR14 Committee[16]) is included in **Fig. 24**. The toughness difference between the base metal and the HAZ tends to increase with increasing base metal toughness. With HIAREST having surface layers of extremely high base metal toughness, it was confirmed that the brittle crack was diverted into the base metal and arrested there without propagating to the bond zone under a high stress of 75 to 100% of the yield stress.

This experimental result suggests that the crack propagation behavior in the welded joint is more strongly governed by the lowest toughness of the HAZ than the magnitude of the base metal toughness. It was confirmed that brittle cracks do not readily propagate in the bond zone of HIAREST as well as conventional steel plates produced by the thermomechanical control process (TMCP).

4.2.2 Properties of steel plates with bead-on-plate welds

Bead-on-plate test specimens were prepared to simulate the thermal effect of fillet welding, for example, on either of the SUF portions of HIAREST. When a single bead line is deposited on a one-side notched ESSO test specimen, a compressive residual stress is developed in the vicinity of the notch, so that the crack may not run straight. To alleviate the compressive residual stress in the test bead, another bead was deposited at 100 mm from the test bead on each side of the test bead, and specimens thus prepared (BOP/HIAREST) were subjected to the temperature-gradient ESSO test. The test results have been marked by the closed triangles ▲ in **Fig. 4**(b).

This bead-on-plate test deposited three beads and forcibly initiated a brittle crack at the center notch, but the brittle crack did not propagate along the weld. In the specimen shown in **Fig. 25**, the brittle crack greatly diverted from the test bead and propagated in a zigzag path with respect to the compressive residual stress reduction beads. The disappearance of shear lips was observed on the transverse section of the weld bead.

4.3 Summary

It was confirmed that the welded joint toughness of HIAREST is governed by its chemical composition and that HIAREST has toughness properties equivalent to those of steel plates having the

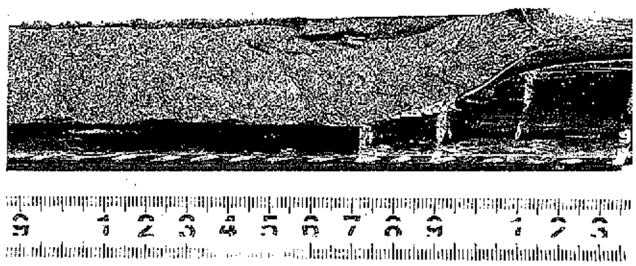


Fig. 22 Fracture and appearance of welded-joint brittle crack propagation test specimen in vicinity of crack arrested point

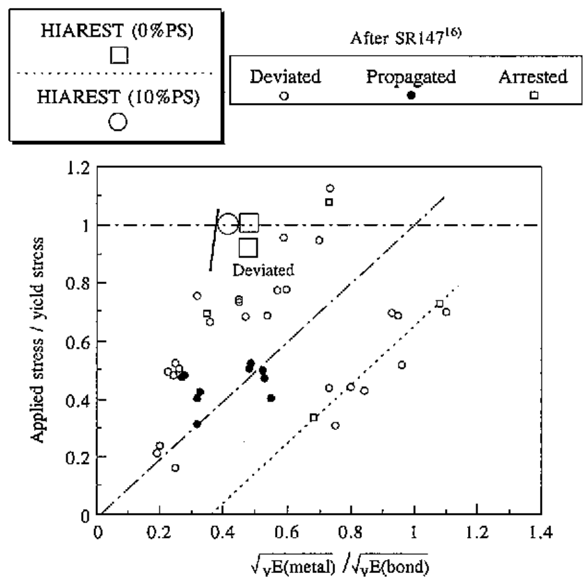
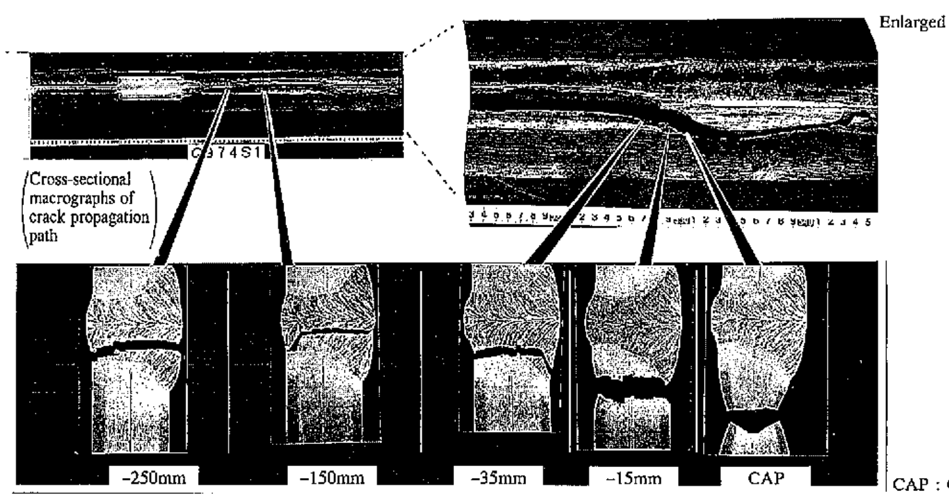


Fig. 24 Effects of toughness ratio of most embrittled zone to base metal and applied stress/yield stress ratio on crack propagation in bond zone of welded joints



CAP : Crack arrest point

Fig. 23 Macrographs of cross sections through crack propagation region of welded-joint brittle crack propagation test specimen

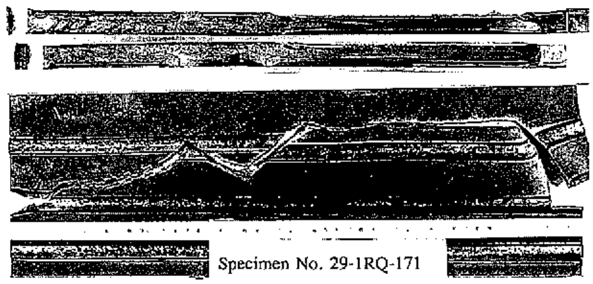


Fig. 25 Appearance of 18-mm thick bead-on-plate test specimen

same chemical composition and produced by the conventional TMCP. Since HIAREST has sufficient toughness in the welded zone, the brittle crack is considered to divert into the base metal without propagating along the welded line. The superior capability of HIAREST to arrest cracks in the base metal is expected to be applied to the welded joint as well.

5. Other Properties of HIAREST

HIAREST was also tested to determine its fatigue life and field fabricability, two important properties for its use in welded structures and similar applications.

5.1 Fatigue resistance properties

Fig. 26 shows the results of axial fatigue test of boxing welded joints (this test is designed to evaluate and simulate fatigue life against the initiation and propagation of a fatigue crack at the weld toe of an additional member fillet welded to a longitudinal member). The S-N diagram (cyclically applied stress versus number of cycles to failure) of conventional 355 N/mm^2 steels shows that HIAREST welded joints are located at the high end of the fatigue life range. The results of axial fatigue test (classical test method for evaluating the fatigue properties of welded joints) of non-load-carrying cruciform joints are shown in **Fig. 27**. HIAREST joints are located at the longer-life side of the curve indicating the failure probability of 95% for HT36 (F.P.95% curve) as published by the Nippon Kaiji Kyokai. This means that HIAREST calls for the same fatigue strength improvement measures as practiced for conventional 355 N/mm^2 steels when applied to actual ship structures.

5.2 Field fabricability

5.2.1 Weldability

The weldability of HIAREST depends on its chemical composition. The results of maximum hardness test (test method for evaluating the rise in hardness of the steel plate surface under the influence of welding) are shown in **Fig. 28** as an example of weldability of HIAREST. Since HIAREST has ultrafine microstructures in its surface layers, its surface hardness is higher than that of conventional TMCP steel plates. The maximum hardness of HIAREST when welded depends on its chemical composition and is equivalent to that of the conventional TMCP steels.

5.2.2 Linear heating property

The linear heating test results of HIAREST are shown in **Fig. 29**. Steel plates are linearly heated to deform them into desired shape for shipbuilding. The linear heating test is designed to simulate the effect of linear heating on the mechanical properties of steel plates. The microstructure of the zone austenitized by linear heating is changed to that dictated by the chemical composition of

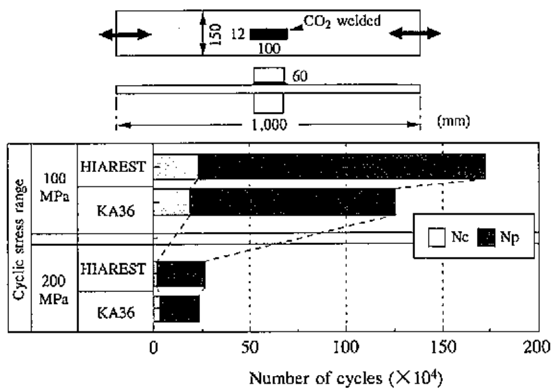


Fig. 26 Axial fatigue test specimen of boxing welded joint and results of axial fatigue test

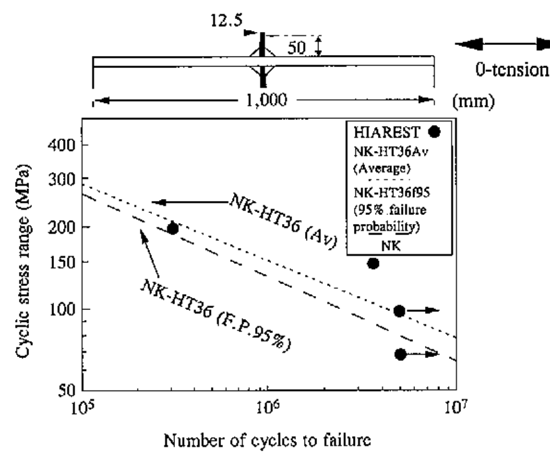


Fig. 27 Fatigue test specimen of non-load-carrying cruciform joint and results of fatigue test

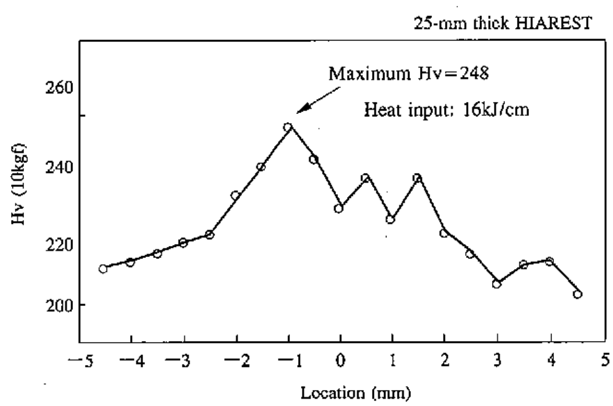


Fig. 28 Results of maximum hardness test

HIAREST, so that its hardness is lower than that of the SUF region not linearly heated. The hardness distribution of HIAREST measured at 1 mm below the plate surface is different from that of the conventional TMCP steel plate and is such that the HAZ is softer than the base metal. The Charpy V-notch impact test results of the

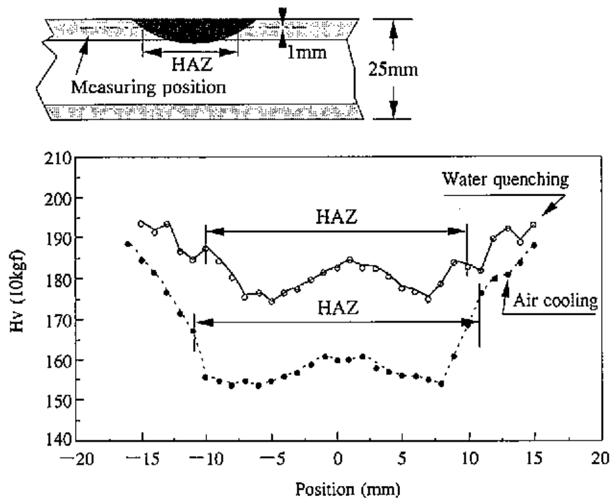


Fig. 29 Hardness distribution of linearly heated zone

zone affected by linear heating reveal little embrittlement and confirm that the zone has sufficient toughness.

5.2.3 Strain aging property

When an 18-mm thick HIAREST steel plate was subjected to a plastic strain of 5%, aged at 250°C for 1 h, and then Charpy V-notch impact tested, it exhibited a transition temperature ($_{v}T_{rs}$) of −112°C. A slight decrease in toughness is noted as compared with a HIAREST steel plate in the plastic strain-free condition that has a transition temperature of −120°C or less. This loss of toughness is small, however. (For example, the toughness reduction range is a maximum of about 30°C in terms of $_{v}T_{rs}$ for conventional low-temperature steel plates and the hull structural steel plate HT50[17].) This means that the cold workability of HIAREST is equivalent or superior to that of conventional TMCP steels.

5.3 Summary

The fatigue properties of welded joints of HIAREST are equal or superior to those of conventional TMCP plate steels and are practically satisfactory.

The weldability of HIAREST is governed by its chemical composition. HIAREST has properties equivalent to those of conventional TMCP steels of the same chemical composition. Since the toughness of linearly heated and strain aged portions is influenced by the microstructure of the base metal, HIAREST has toughness properties superior to those of conventional TMCP steels.

6. Conclusions

The authors developed a new type of steel plate, designated HIAREST. Surface layers of ultrafine microstructure are formed to ensure shear lip development during brittle crack propagation and markedly improve crack arrest performance. The crack arrest performance and service performance of HIAREST were studied. The following findings were obtained:

(1) HIAREST has an extremely high crack arresting capability.

(2) Removal of one of the two SUF regions allows HIAREST to retain its extremely high crack arresting capability as compared with steel plates produced by the conventional TMCP.

(3) When HIAREST was tested by the bead-on-plate method, the brittle crack did not propagate in the weld zone despite the adoption of the test method of alleviating the effect of residual stress on the crack propagation. The weld part exhibited almost the same crack arresting performance as the base metal.

(4) The effect of shear lip formation in improving the crack arresting performance can be quantified. When the SUF thickness is predicted to diminish in a corrosive environment, for example, HIAREST can be selected by compensating for the reduction in the SUF thickness.

(5) Welded joint toughness and weldability are governed by the chemical composition of steel plates. HIAREST has properties equivalent to those of the conventional TMCP steel.

(6) Where linearly heated and strain aged, HIAREST is as tough as conventional TMCP steels because it has a microstructure similar to that of the conventional TMCP steel as far as brittle crack initiation is concerned. Once HIAREST has a brittle crack initiated, it can arrest the crack while it is still short. For this reason, HIAREST has practical toughness properties superior to those of the conventional TMCP steel.

HIAREST and the conventional TMCP plate steel EH36 were subjected to a plastic strain of 10% and comparatively evaluated for crack arresting performance. The following results were obtained:

(1) The plastic strain of 10% made it difficult for EH36 to arrest long cracks at 0°C.

(2) When subjected to the plastic strain of 10%, HIAREST was confirmed to have crack arresting performance superior to that of EH36 without plastic strain.

Where conventional steel plates are unable to arrest the propagation of brittle cracks when subjected to plastic strains in large ship collisions or large earthquakes, HIAREST is expected to exhibit sufficient crack arresting performance to provide greater safety in such cases.

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