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Development of t100 mm-YP460 N/mm² Class Steel Plate with Excellent Brittle Crack Arrestability (ARRESTEX™) for Large Container Ships

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Abstract:

YP460 N/mm² class steel with a thickness of 100 mm, which has excellent brittle crack arrestability (ARRESTEX™) for large container ships, has been developed. For the developed steel, optimization of alloy composition, controlled rolling conditions and controlled cooling technology using Super-OLAC™ (On-Line Accelerated Cooling) were applied. The developed steel shows excellent brittle crack arrestability by controlling texture, in addition to improving toughness by refining crystal grains. The developed steel with a thickness of 100 mm sufficiently satisfies the target value for brittle crack arrest toughness ($Kca_{(-10^\circ C)} \geqq 8\,000$ N/mm$^{3/2}$) at the hull design temperature.

1. Introduction

The number of maritime shipping containers handled has increased rapidly in recent years, supported by the economic growth of the Asian nations, such as China [1]. Moreover, a response to stricter regulations on ship exhaust gas, which is a cause of global warming, and further improvement of transportation efficiency are also demanded in maritime logistics utilizing container ships. In order to respond to these requirements, the size of container ships is increasing year by year. Around 2000, the loading capacity of the largest container ship was 8 000 TEU (TEU: Twenty-foot Equivalent Unit, loading capacity converted to 20-foot containers), but ultra-large-scale container ships with capacities exceeding 20 000 TEU have appeared recently. According to this upscaling of container ships, high strength steel plates are used in ship side upper chord members. The strength of these steel plates has increased from YP355 N/mm² class to YP390 N/mm² class or YP460 N/mm² class, and YP460 N/mm² class steel with a plate thickness of 100 mm has been applied to the hatch side coamings of recent ultra-large-scale container ships.

For ensuring safety, which is the most important issue for ships, excellent resistance to brittle crack initiation is required for the steel plates applied to hull structure, and high brittle crack arrestability is also demanded in order to prevent brittle crack propagation in the hull structure even if crack initiates. In conventional-scale container ships in which comparatively thin steel plates with a thickness of approximately 35 mm, have been applied, brittle crack propagation is prevented in base metal by applying Grade E shipbuilding steel (Steel guarantee mechanical properties at −40°C), since brittle crack is deflected to the base metal by the influence of residual stress, *etc*., even if crack initiates in a weld parts [2, 3]. However, it has been indicated that brittle cracks propagate along the weld line if the plate thickness increases to around 70 mm with increase in hull structure size, which may cause fatal damage to the hull structure in the worst case [4]. This issue had become a problem for further upsizing of container ships.

Against this background, when a steel plate with a

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thickness exceeding 50 mm is applied to the hull structure, crack arrest design which "propagation of brittle cracks can be prevented in case of crack initiation" is required for container ships contracted for construction after January 2014 by the International Association of Classification Societies (IACS) [5, 6]. As a concrete response to this requirement, steel plates with excellent brittle crack arrestability where "the brittle crack arrest toughness value ($Kca_{(-10°C)}$) exceeds 6 000 N/mm$^{3/2}$ at −10°C" have been applied, in addition to a structural discontinuity created by providing a crack arrest hole or performing welding with the weld lines offset by at least 300 mm in the hatch side coaming part and deck plate part, as shown in **Fig. 1**. In December 2019, a Kca value up to a plate thickness of 100 mm was also indicated [7], therefore a higher brittle crack arrestability is required with the increase in plate thickness, and a $Kca_{(-10°C)}$ value exceeding 8 000 N/mm$^{3/2}$ is required for steel plates applied to hatch side coaming members with plate thicknesses of 80 mm< t≤100 mm. This regulation is scheduled for application to large container ships contracted for construction from January 2021.

Improvement of the brittle crack arrestability of steel plate has been studied mainly from the viewpoint of improvement of the property by grain refinement, and many results have been reported [8–10]. In addition to improvement by the conventional approach with grain refinement, JFE Steel developed a technology which dramatically improves brittle crack arrestability by focusing on texture controlling technology, which has hardly been utilized in thick steel plates [11]. YP460 N/mm^2 class ARRESTEX^{TM} for ultra-large container ships with a thickness of 100 mm has succeeded in expanding the thickness by stricter control of the manufacturing conditions based on the technology reported previously [12], and the properties are indicated in this report.

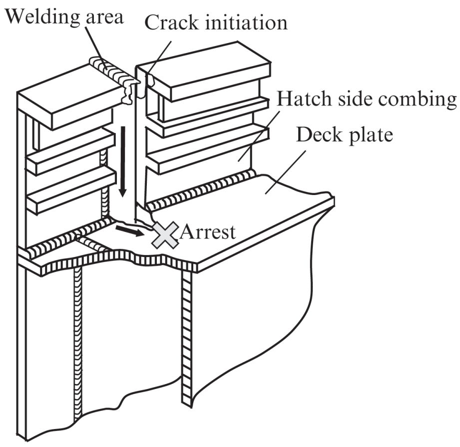

Fig. 1 Container ship superstructure and concept of brittle crack arrest design

2. Method of Improving Brittle Crack Arrestability

For improving brittle crack arrestability, enhancing low temperature toughness by grain refinement utilizing the thermo-mechanical control process (TMCP) is extremely effective. However, required brittle crack arrestability is not stably obtained in the steel plate with a thickness exceeding 70 mm, since grain refinement is insufficient in the inside of the plate by hot rolling, thus new direction of microstructural controlling was necessary as an alternative to the conventional technology. Therefore, in addition to conventional grain refinement technology, JFE Steel focused on texture control technology, which has hardly been utilized in thick steel plates, and developed an ultra-heavy thickness plate with high brittle crack arrestability.

The concept of texture control and brittle crack arrestability are described as follows. Brittle crack propagates along {100} plane, which is the cleavage plane of bcc crystallographic structure. An initiated brittle crack will propagate in the direction perpendicular to the direction of principal stress, as shown in **Fig. 2** (a) if orientations are random like the conventional steel. On the other hand, in the developed steel, a brittle crack progresses by branching in a direction 45° from the direction of principle stress, as shown in Fig. 2 (b), which can increase crack propagation resistance. Handa *et al*. studied the influence of texture intensity on brittle crack arrestability, and investigated the contributions of the Charpy transition temperature (vTrs) and texture for the brittle crack arrest temperature $T_{K(6\,000)}$; temperature at which Kca becomes 6 000 N/mm$^{3/2}$. It is indicated that brittle crack arrest temperature: $T_{K(6\,000)}$ is strongly related to the following Eq. (1), which is called the Y index, and it is clarified that brittle crack arrestability became higher in absolute value of the Y index [13].

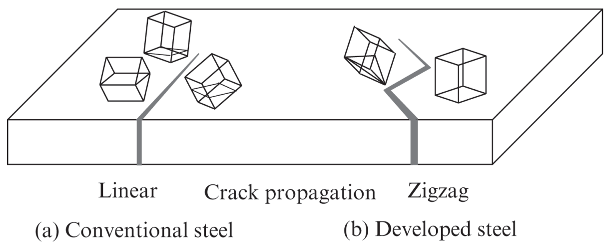

Fig. 2 Concept of improving brittle crack arrestability by texture control

Table 1 Chemical composition of developed steel plate

Steel	C	Si	Mn	P	S	Others	*C*eq (IIW)	P_{CM}
Developed	0.06	0.15	1.93	0.004	0.001	Cu, Ni, Cr, Nb, Ti	0.47	0.20
Specification of EH47-BCA (IACS UR W31)	≦0.18	≦0.55	0.90-2.00	≦0.020	≦0.020		≦0.55	≦0.24

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

$$Y = vTrs - 12 \times I_{\{100\}} - 22 \times I_{\{211\}} \quad \text{.............. (1)}$$

$I_{\{100\}}$: Intensity ratio of {100} planes of tested steel plate and reference sample
$I_{\{211\}}$: Intensity ratio of {211} planes of tested steel plate and reference sample

Improvement of brittle crack arrestability by toughness improvement utilizing the grain refinement effect becomes even more difficult with the plate thickness of 100 mm. Therefore, according to the above equation, it is necessary to increase the strain introduced in the plate center-of-thickness (1/2 t), and to control the texture distribution so as to increase {100} and {211} textures at 1/2 t. Furthermore, in a study of the brittle crack arrestability of plain carbon steel plates, Tsuyama *et al*. showed that plates with a highly orientated {100} and/or {211} texture parallel to the plate surface from the 1/4 t to the 1/2 t region of the plate display a split-nail shaped fracture surface morphology at the brittle crack arrest position, and the decrease in the stress intensity factor at the crack tip accompanying crack propagation is larger in plates that display the split-nail shaped fracture surface morphology in comparison with those that display the thumbnail shaped fracture surface morphology [14]. These study results suggest the possibility that a high level of brittle crack arrestability, which could not be achieved by the conventional grain refinement approach, can be obtained by utilizing texture.

3. Base Metal Properties of Developed Steel

3.1 Chemical Composition and Manufacturing Method

The chemical composition of the developed steel is shown in **Table 1**. The composition was designed to achieve a low value of the weld crack susceptibility index (P_{CM}), considering weldability in shipyards. In addition, all these compositions satisfy the specification of UR-W31 in the IACS Unified Requirements as revised in December 2019, as shown in the table.

The steel plate with a thickness of 100 mm is produced by hot rolling from a slab obtained by continuous casting. In order to obtain the target microstructure in the plate center-of-thickness, the heating and rolling conditions in TMCP, which is a representative manufacturing process for heavy-thickness steel plates, and the cooling conditions of the *Super*-OLAC^{TM} (On-Line Accelerated Cooling) after rolling were strictly controlled in the optimum range.

3.2 Mechanical Properties

The microstructure of the developed steel is a bainite single-phase structure, as shown in **Photo 1**. The tensile strength of the developed steel (thickness: 100 mm) utilizing texture control and a comparison steel (thickness: 70 mm) using only the conventional grain refinement technology are shown in **Table 2**, and the results of the Charpy impact test are shown in **Table 3**. Both the strength and the toughness of the developed steel amply satisfy the target properties of Grade E YP460 N/mm^2 steel at all test positions. At 1/2 t, the toughness values of the conventional and developed steels are similar, but the developed steel shows a larger absolute value of the Y index, which also considers the contribution of the texture.

The results of the drop weight test of the developed steel are shown in **Table 4**. The test was carried out in accordance with ASTM E208 using a P-3 type test piece. The test was performed with samples taken from the surface, 1/4 t and 1/2 t positions of the steel plate, and the nonductile transition temperature (NDTT) was obtained. Satisfactory results were obtained, as NDTT was −80°C at the surface and 1/4 t positions and −70°C at the 1/2 t position.

Table 5 shows the test conditions and test results of the CTOD (Crack Tip Opening Displacement) test of

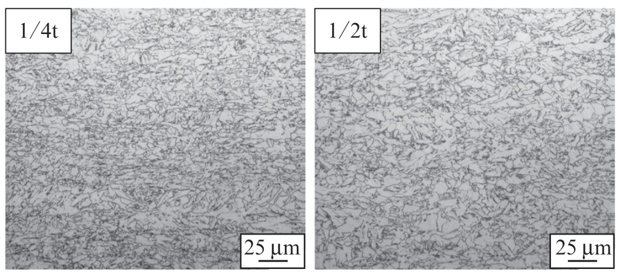

Photo 1 Microstructures of developed steel plate

Table 2　Tensile properties of developed steel plate

Steel	Thickness (nm)	Position	Direction	YP (N/mm^2)	TS (N/mm^2)	EL (%)
Developed	100	1/4t	C	483	594	26
		1/2t	C	472	585	24
Conventional	70	1/4t	C	478	582	24
Specification of EH47 (IACS UR W31)				≧460	570～720	≧17

Table 3　Charpy impact properties of developed steel plate

Steel	Thickness (nm)	Position	Direction	vE_{-40} (J)	vTrs (˚C)	Y index
Developed	100	1/2t	L	293	−79	−147
Conventional	70	1/2t	L	298	−71	−118
Specification of EH47 (IACS UR W31)				≧75		

Y index = vTrs−12×$I_{(200)}$−$I_{(211)}$[13)]

Table 4　Results of NRL drop weight test

Steel	Position	Direction	Drop weight energy (N·m)	NDTT (˚C)
Developed	surface	L	402	−80
	1/4t	L	402	−80
	1/2t	L	402	−70

Table 5　CTOD test results of base metal

Steel	Specimen size	Direction	Test temperature (˚C)	CTOD (mm)
Developed	B×B (B = 100 mm)	L	−10	0.89 ($\delta^M{}_u$) 1.59 ($\delta^M{}_u$) 2.81 ($\delta^M{}_u$)

the base metal. The test was conducted in accordance with ISO 12135 using a full-thickness B × B test piece. Three tests were performed under the same conditions at a test temperature of −10˚C. From the test results, low values did not occur in the CTOD test of the base metal, in spite of the ultra-heavy plate thickness of 100 mm, and satisfactory results were obtained.

3.3 Weldability

The developed steel was designed to achieve a low value of the weld crack susceptibility index P_{CM} considering weldability in shipyards, and weld cracking sensitivity was evaluated without preheating. Using the developed plate with a thickness of 100 mm, a y-groove weld cracking test was carried out with a welding heat input of 1.5 kJ/mm in accordance with JIS Z 3158 at test temperatures of 20˚C and 0˚C and a humidity of

Table 6　y-groove weld cracking test results

Welding atomosphere	Crack ratio (%)		
	Surface crack	Root section	Cross section
20˚C, RH60%	0 0 0	0 0 0	0 0 0
0˚C, RH60%	0 0 0	0 0 0	0 0 0

Welding material: LB-62UL (4.0 mmϕ), Kobe Steel, Ltd.
Welding condition: 170A-22V-150 mm/min (1.5 kJ/mm)

60%. The test results are shown in **Table 6**. It was found that the developed steel has excellent cold crack resistance, as no surface cracks, root section cracks or cross-sectional cracks occurred even at the test temperature of 0˚C.

3.4 Brittle Crack Arrestability

A brittle crack arrestability value of $Kca_{(-10^\circ C)}$ ≥8 000 N/mm$^{3/2}$ is required in steel plates with thicknesses exceeding 80 mm. **Figure 3** shows the results of a temperature gradient type standard ESSO test of the developed steel with thicknesses of 70 mm and 100 mm. For comparison, the figure also shows the test results for a conventional steel plate with a thickness of 70 mm, in which only grain refinement was used. The conventional steel displayed a Kca value at −10˚C of approximately 6 000 N/mm$^{3/2}$, in spite of the thinner plate thickness of 70 mm, and thus fails to achieve the target of $Kca_{(-10^\circ C)}$ ≥8 000 N/mm$^{3/2}$. In contrast, the developed steel, in which texture control was used, achieved the target by a wide margin. **Photo 2** shows photographs of the fracture surfaces after the standard

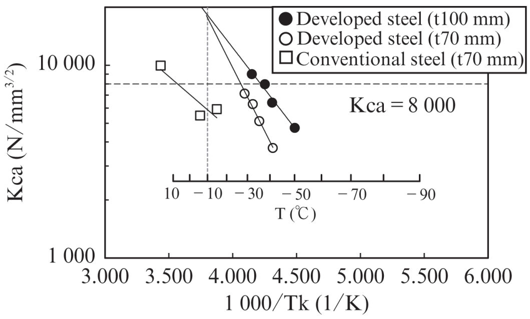

Fig. 3 Results of temperature gradient type standard ESSO test

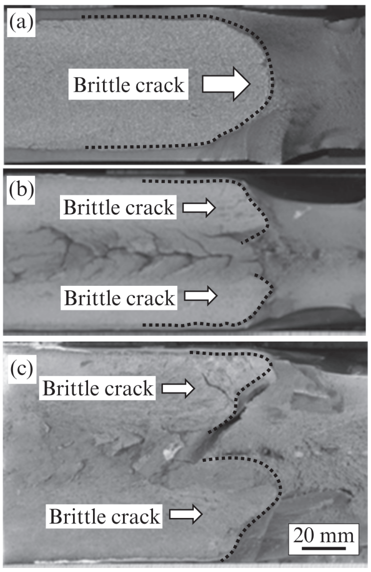

Photo 2 Comparison of fracture appearance of temperature gradient ESSO specimens
(a) Conventional steel (t70 mm) (b) Developed steel (t70 mm)
(c) Developed steel (t100 mm)

ESSO test. Although the conventional steel displays the general thumbnail shaped fracture surface, as shown in (a), the developed steel shows a split-nail shaped fracture surface as a result of its increased crack propagation resistance in the plate center-of-thickness, as can be seen in (b). The developed steel also maintained this fracture surface morphology at the plate thickness of 100 mm, as shown in (c). Based on these results, it can be understood that texture control fully demonstrates its effectiveness in improving brittle crack arrestability, even with the plate thickness of 100 mm.

In conventional steel plates using only grain refinement, the Kca value decreases as the plate thickness increases, and it is impossible to achieve Kca of 8 000 N/mm$^{3/2}$ even with the smaller plate thickness of 70 mm. The developed steel can secure a high Kca value when the plate thickness is increased from 70 mm to 100 mm because texture control is also used. It is also considered possible to obtain plates that amply satisfy the required Kca value by utilizing this technique, even assuming further increases in plate thickness in the future.

4. Welded Joint Properties of Developed Steel

4.1 Welding Conditions

The performance of multilayer welded joints of the developed steel was evaluated. The welding conditions are shown in **Table 7**. Joints were fabricated by gas metal arc welding (GMAW) and submerged arc welding (SAW) with heat inputs of 1.5 kJ/mm and 5.0 kJ/mm, respectively.

4.2 Welded Joints

The results of a tensile test and Charpy impact test of the welded joints are shown in **Table 8**. The results of both tests fully satisfied the target values. A CTOD test was also performed to evaluate the fracture toughness of the joints. The test conditions and results are shown in **Table 9**. For reference, the specification of the DNV GL ship classification society, in which the joint CTOD value is specified, is shown together with the test results. Satisfactory results which satisfy the specification by a wide margin were obtained, confirming that the developed steel plate has an excellent brittle fracture initiation resistance.

Table 7 Welding conditions

	GMAW	SAW
Welding material	DW-460L (1.2 mmϕ) (Kobe Steel, Ltd.)	KW-101B (4.0 mmϕ) (Kobe Steel, Ltd.)
Shield gas/Flux	CO_2	KB460 (Kobe Steel, Ltd.)
Groove shape	single bevel groove Groove angle: 35° Gap: 10 mm	single bevel groove Groove angle: 35° Gap: 10 mm
Welding condition	280A-32V-360 mm/min (1.5 kJ/mm)	650A-32V-260 mm/min (5.0 kJ/mm)

Table 8 Mechanical properties of welded joint

	TS	F.L. vE-20 (J)		
		Surface 2 mm	1/2t	Root 2 mm
GMAW	615	136	99	194
SAW	647	298	299	255
Specification of EH47 (IACS UR W31)	570～720	≧64		

Table 9 CTOD test results of welded joint

	GMAW	SAW
Heat input (kJ/mm)	1.5	5.0
Specimen size	B×B (B = 100 mm)	B×B (B = 100 mm)
Noch position	CG-HAZ	CG-HAZ
Test temperature (°C)	−10	−10
CTOD (mm)	0.47 ($\delta^M{}_u$) 0.90 ($\delta^M{}_u$) 0.93 ($\delta^M{}_u$)	0.44 ($\delta^M{}_u$) 0.61 ($\delta^M{}_u$) 0.82 ($\delta^M{}_u$)
Specification of EH47-BCACOD (DNV-GL)	min≧0.18, ave≧0.20	

5. Conclusion

A new YP460 N/mm^2 class steel plate ARRESTEX^{TM}, which provides extremely high brittle crack arrestability and weldability even with an ultra-heavy thickness of 100 mm, was developed by utilizing precise texture control in addition to the conventional grain refinement technology. It is considered possible to manufacture plates that amply satisfy brittle crack arrestability requirements, even assuming the plate thickness is expanded further in the future and higher Kca values are required.

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