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YP 460 N/mm^2 Class Heavy Thick Plate with Excellent Brittle Crack Arrestability for Mega Container Ships

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Abstract

YP460 N/mm^2 class heavy thick plate with excellent brittle crack arrest toughness for mega container ships has been developed. Prior to development, the effect of metallurgical factors on arrestability of high strength steel and a method to quantify the effective grain size were studied. On the basis of these findings, we have found the optimum chemical compositions and TMCP conditions to achieve high arrest toughness. Superior arrestability of the developed steel was also demonstrated in large scale fracture tests that simulate the real structure. In addition, simple method to evaluate arrestability in replace of conventional ESSO tests was established.

1. Introduction

In recent years, along with the progress of globalization of market, the amount of marine transportation continues to grow on a global scale, and the needs of increasing ship size and their performance are growing, intending alleviation of environmental load and saving of transportation cost. In particular, a trend in increase in size of containership is remarkable and recently, mega containerships of 14 000–20 000 TEU class (twenty-foot equivalent unit: number of containers expressed in the number of 20 feet container as a unit) have come to be built. A container ship has big openings on the upper deck and, for the hatch side combing, a high strength heavy thick steel plate is used in order to maintain hull configuration. However, in using heavy thick steel plates, sufficient attentions have to be paid to deterioration of safety due to decline in brittle fracture resistance characteristics, increase in ship weight and increase in welding work load.

As for the safety of the brittle fracture, it is pointed out that in addition to the prevention of the occurrence of the brittle crack, prevention of crack propagation is very important even if it takes place in a contingent case.[1] Systematic studies on the behavior of brittle crack propagation have been conducted so far by the SR Committee of the Shipbuilding Res. Assoc. of Japan and the likes.[2, 3] It has been considered that on the basis of its study results, even if a brittle crack is developed due to the crack propagation toward the base plate influenced by the residual stress of the welded joint of steel plates 40 mm or less in thickness, the safety of a welded joint is secured by equipping the base material with brittle crack propagation halting capability (hereinafter termed as arrestability or arrest toughness).

However, in the study designed for steel plates with yield point (YP) of 390 N/mm^2 or more and 65 mm or more in thickness, it became clear that it is difficult to halt the propagation of a long crack even on a steel plate of conventional material for shipbuilding that satisfies the Charpy impact property of EH-grade.[4] Triggered by the study in Japan, an industry–academia collaboration joint research, conducting a large scale test on arrestability was started. On the basis of the result of the research, a guideline was shown,[5] which states that for steel plate of 75 mm or below in thickness, brittle crack can be arrested if the arrest toughness (Kca) is 6 000 N/mm$^{1.5}$ or more.[5] On the basis of these sequential findings, Nippon Kaiji Kyokai has enacted arrestability assurance standard,[6] which was incorporated to UR (Unified Requirements) of International Association of Classification Societies (IACS).[7]

Taking the above background into consideration, Nippon Steel & Sumitomo Metal Corporation has developed YP460 N/mm^2 steel, which has higher strength than the conventional YP390 N/mm^2 steel

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with excellent arrest toughness and has applied it to actual ships.[8, 9] This article reports the outline of the microstructure-controlling technology established for improving arrest toughness and the characteristics of the developed steel.

2. Brittle Crack Arrest Toughness Improving Technology

In general, characteristics that influence toughness often reveal the brittle-crack-initiation property, and the guideline for improvement is almost entirely summarized in the following three points.

① Refinement of effective crystalline grain diameter (d_{eff})
② Improvement of toughness of matrix (addition of Ni, reduction of solute N, and so on)
③ Reduction of fracture-initiating brittle phase (nonmetallic inclusions, precipitates, M-A (Martensite Austenite constituent) and so on)

Nippon Steel & Sumitomo Metal has conducted extensive study on the influence of various factors on arrestability mainly using laboratory-processed steel and confirmed that the concept of improving arrestability agrees basically with the aforementioned. Effect of refining grain of ① is understood as the result of fracture-developing energy being increased as the total tear ridge length per unit area of a fractured surface increases.[10] The effect of addition of Ni of ② has been known since before,[11] and it is confirmed that its effect practically differs from the microstructure-refining effect. This is presumed to be attributed to the increase in mobility of dislocation due to solute Ni.[12] However, from the viewpoint of alloy cost, Ni is not used positively in many cases. Although the brittle phase mentioned in ③ has also been confirmed to influence arrestability, its influence is small as compared with its influence on other crack-initiation characteristics. Besides the charactristics mentioned above, it is known that texture also influences arrestability.[13] However, excessive development of texture generates a possibility of causing disturbances to production and a problem of material anisotropy. On the basis of the above findings, it was decided to mainly study the refining of d_{eff} of ① in this development.

d_{eff}, which governs arrestability, is considered to be the average grain diameter. However, till date, the unit of the structure of high strength steel mainly composed of bainite has not been identified clearly. Then, crystalline orientation analysis on the fracture surface of a temperature gradient type ESSO test piece was conducted with EBSD (Electron Backscattering Diffraction) method. Also, precise study on the relationship between d_{eff} and the microstructure was conducted. It was confirmed that when the region where crack propagated mostly in a flat manner is taken as a unit fracture facet, the facet is considered to represent the crystalline grain, and arrestability is arranged by the average size of the unit fracture facet (grain size), consisting of a packet of bainite and several ferrite (α) grains.

Furthermore, taking into consideration as shown in **Fig. 1** that it sometimes happens that a big difference in brittle crack propagation resistance takes place even if the crystalline misorientation is the same, a new index (crack propagation deviation angle) that denotes propagation resistance was proposed, and it was found that the boundary with the deviation angle of 25° or more corresponds to the boundary of a fracture facet unit. **Figure 2** shows an example of the analysis. Conventionally, the average grain diameter sought by EBSD method is smaller than the fracture facet unit and has poor relationship with the temperature $T_{Kca6000}$, where Kca becomes 6000 N/mm^2. However, d_{eff} calculated on the basis of the above finding is almost equal to a fracture facet unit and, as **Fig. 3** shows, the relationship with $T_{Kca6000}$ is good.

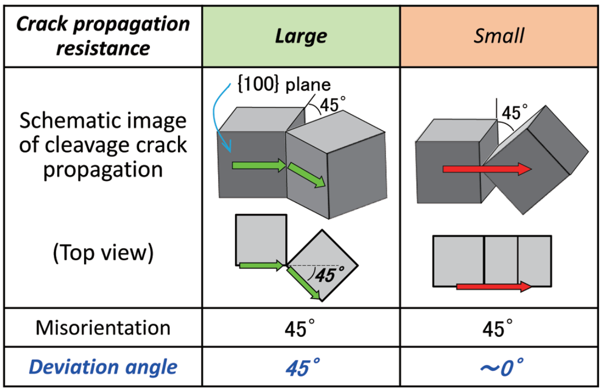

Fig. 1 Basic concept of brittle crack propagation resistance

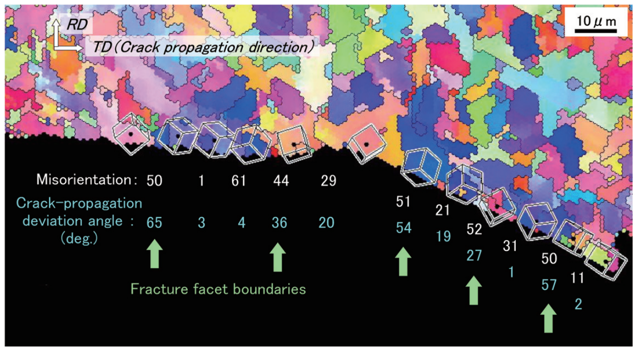

Fig. 2 Example of analysis to estimate effective grain size by EBSD

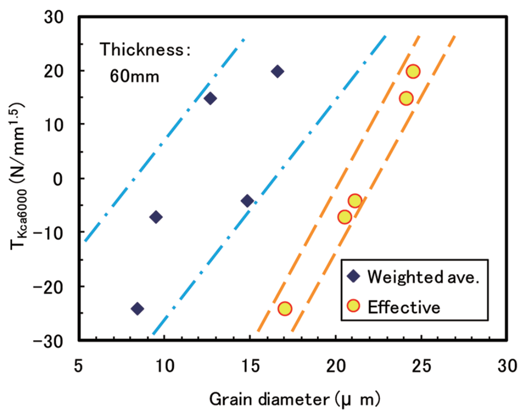

Fig. 3 Relationship between grain diameter estimated by EBSD and $T_{Kca6000}$ obtained by ESSO test

TMCP (Thermo-Mechanical Control Process) is known as a means to refine the microstructure. Then, to find out the condition that refines the aforementioned d_{eff} most effectively, an overall study was conducted, which included a study on the effect of the rolling temperature and the reduction ratio at each rolling pass, needless to mention of the study on the effects of general slab heating, controlled rolling (CR), and accelerated cooling conditions. The main feature of the study is as follows;

1) Compatibility of refining initial austenite (γ) with a solid solution of alloying elements by controlling the heating temperature to a narrow range

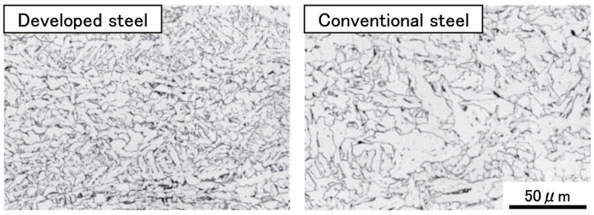

Fig. 4 Microstructures of developed steel and conventional steel

2) Effective accumulation of strain in the γ phase by optimizing the rolling pass schedule (temperature and reduction ratio) of CR
3) To lower transformation temperature and to refine d_{eff} by accelerated cooling after CR

Figure 4 shows the microstructures of the conventional steel (YP390 steel produced with conventional TMCP) and the developed steel (YP460 steel produced under the aforementioned condition). It is known that the grain is clearly refined in the developed steel. Consequently, arrestability is remarkably improved.

3. Mechanical Properties of the Developed Steel

3.1 Base metal mechanical properties

Based on the above guidelines, steel plates of 80 mm and 90 mm in thickness were produced. The chemical compositions and the mechanical properties of the base metal are shown in **Tables 1** and **2**. The base metal satisfies the aimed mechanical properties of strength, elongation, and Charpy impact value. Furthermore from **Fig. 5**, it is known that the arrest toughness evaluated by the standard ESSO test also shows satisfying values. **Figure 6** shows the microstructures of the developed steel at t/4 (t: plate thickness) and t/2. Both show microstructure composed of fine α and bainite and this microstructure is considered to produce excellent toughness and arrestability.

To assess the arrestability in an actual construction, a large scale fracture test using an 8000 ton tensile testing machine was conducted. An example of the test results is shown in **Fig. 7**. This test simulates a case wherein a hatch side combing (YP460) is designed to arrest brittle crack propagation initiated at a high heat input welded joint of an upper deck (YP390). A crack that penetrated the test plate (YP460) at −10°C was arrested at the point approximately 30

Table 1 Typical chemical compositions of steels developed

(mass%)

Thickness (mm)	C	Si	Mn	P	S	Others	Ceq*
80	0.09	0.10	1.61	0.008	0.002	Mo, Nb, V, Ti, B	0.38
90	0.09	0.18	1.62	0.009	0.003	Cu, Ni, Mo, Nb, V, Ti, B	0.44

*Ceq=C+Mn/6+(Cu+Ni)/15+(Cr+Mo+V)/5

Table 2 Mechanical properties of steels developed

Thickness (mm)	Tensile test (t/4)			Charpy impact test (t/4)	ESSO test
	YP (N/mm^2)	TS (N/mm^2)	El (%)	$vE_{-40°C}$ [ave./min.] (J)	$Kca_{-10°C}$ ($N/mm^{1.5}$)
80	499	592	27	293/289	8292
90	500	587	28	282/272	10226
Specification	≧460	570–720	≧17	≧53/37	≧6000

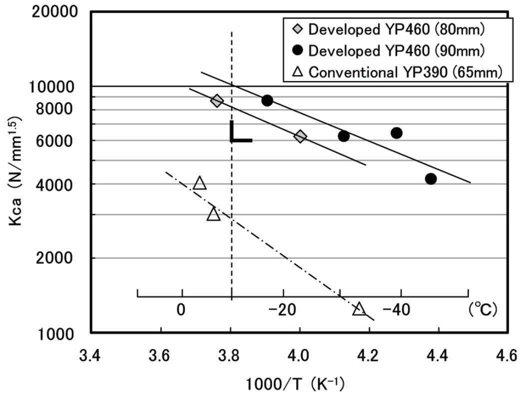

Fig. 5 Results of temperature gradient type ESSO test

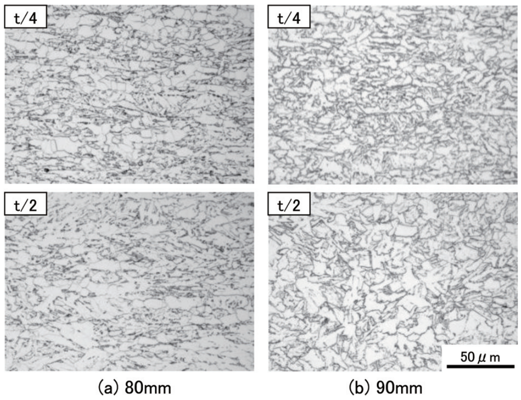

Fig. 6 Microstructures of steels developed

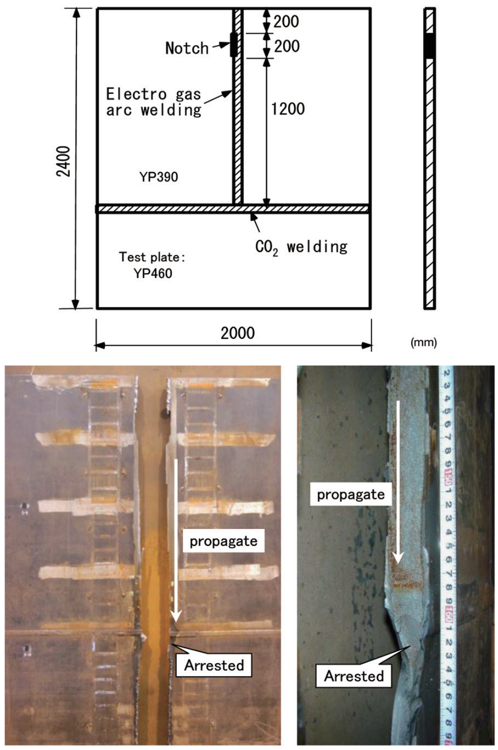

Fig. 7 Example of large scale fracture test

Table 3 Welding conditions and mechanical properties of welded joints

Thickness (mm)	Welding consumable	Welding conditions	Tensile test		Charpy impact test (t/4)			Deep notch
			TS	Fracture	$vE_{-20°C}$ [ave.] (J)			$Kc_{-20°C}$
			(N/mm²)	position	WM	FL	FL + 1 mm	(N/mm$^{1.5}$)
80	SF-47E *(1.2 mmφ)	Groove angle: 40° Gap: 5 mm	633	Base plate	104	139	157	5234
90	SB41 *(backing material)	300A, 31V, 290 mm/min, 1.9 kJ/mm, 100% CO_2	676	Base plate	105	108	165	–
Specification			≧570	–	≧53			≧3580

* Nippon Steel & Sumikin Welding Co., Ltd. WM: Weld metal, FL: Fusion line

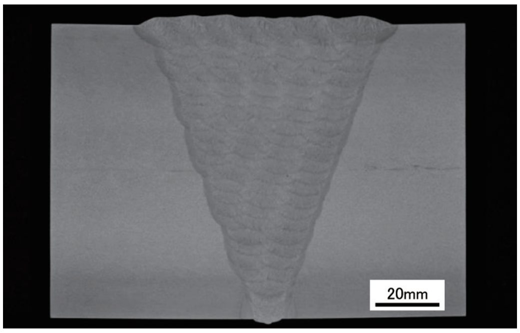

Fig. 8 Macrostructure of welded joint

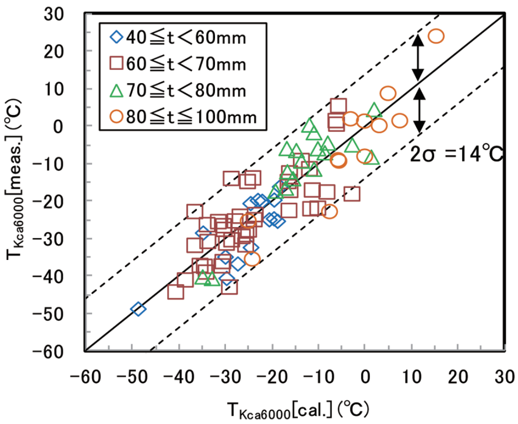

Fig. 9 Relationship between $T_{Kca6000}$ [cal.] and $T_{Kca6000}$ [meas.]

mm apart from the crack initiation point and the excellent arrestability as a part of a construction was confirmed.[8)]

3.2 Mechanical properties of welded joint

To assess the mechanical properties of a welded joint of the developed steel, a multi-layer- joint welded with gas-metal-arc welding was arranged. In **Table 3**, the welding conditions and the result of the assessment of the mechanical properties of the welded joint are shown, and an example of the macrostructure of the welded joint is shown in **Fig. 8**. Both the tensile strength and the Charpy energy absorption values satisfy the aimed values. Furthermore, for a steel plate of thickness of 80 mm, a deep-notch test (test piece of 480 mm in width with a notch of 0.1 mm in width and 240 mm in length mechanically processed lengthwise in the weld direction in the center of the welded joint surface) was conducted. The result shows that the developed steel has the fracture toughness value (Kc) at −20°C of above 5000 N/mm$^{1.5}$ and is equipped with excellent brittle crack initiation properties.

4. Simplified Assessing Method for Brittle Crack Arrest Toughness

To assess the arrest toughness of a steel plate, it is necessary to conduct pluralities of the ESSO test using large square test pieces of 500 mm with original thickness for each plate. The cost of the test is high and implies a number of problems like causing a bottle neck in a production process, exerting influence upon production capacity. Accordingly, establishment of a simplified assessing method replacing ESSO method has been sought for. For the purpose, small various test pieces were taken from all steel plates of different thickness of YP390–460 class, varying in thickness from 40 to 100 mm and the relationship with ESSO test results was studied. Consequently, it was found that the test method comprising of the combination of NRL drop-weight test executed for the surface layer and V-notch Charpy impact test executed for the t/4 part is appropriate and a model of estimating $T_{Kca6000}$ has been worked out, which consists of nil-ductility transition temperature (NDTT) obtained by the drop-weight test and the fracture appearance transition temperature (vTrs) as parameters. **Figure 9** shows the relationship between the calculated values and the measured values of $T_{Kca6000}$. Errors are controlled to within ±14°C and the accuracy of estimation is excellent. On the basis of this method, a criterion for the judgment of acceptance of arrestability based on small scale test has been established.

5. Conclusion

Upon developing YP460 steel for mega container ships, a microstructure-controlling technology to improve brittle crack arrest toughness has been established by fully utilizing the microscopic crystalline orientation analysis up to large scale fracture test. Furthermore, a simplified method of assessing arrestability replacing the conventional ESSO method has also been established. The developed steel has achieved the actual amount of shipping of approximately 30000 tons up to present and the production structure to meet the future growth of demand is being arranged.

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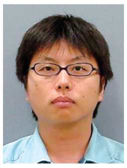

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