Characteristics of Brittle Crack Arrest Steel Plate for Large Heat-input Welding for Large Container Ships

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Once it happens, brittle fracture in the hatch coaming parts around the deck openings of container ships causes serious structural damage that could potentially result in both fatalities and environmental damage. With this in mind, ships are designed and constructed so as to ensure that brittle crack does not occur. Further, if by chance it does occur, having a back-up function for arresting brittle crack included in the steel plate is essential. This report describes the characteristics of KE36 class brittle crack arrest plates. Improvement in brittle crack arrestability was achieved by the refinement of crystal grains, which is a result of strictly temperature-controlled TMCP (Thermo Mechanical Control Process).

Introduction

With the recent increase in the volume of marine transport, container ships are becoming larger. Now, very large ships that can carry more than ten thousand containers have been built. A container ship has a structure with a large opening on its upper deck and its hull girder constructed with an open cross-section. This requires container ships to have the highest longitudinal strength among large merchant ships. In order to ensure longitudinal strength while upsizing its hull, each container ship has a hatch side coaming surrounding its deck and an upper deck, both thickly built adopting steel plates no thinner than 50mm[1)].

The interior of a thick plate, however, is in a plane strain state with the plastic region decreased in size. As a result, a stress greater than its yield stress is generated, and cracks propagate more easily. Brittle fractures, once occurring in the hatch coaming part around the deck openings of a container ship, can cause serious structural damage, with the potential for both fatalities and environmental damage. With this background, ships are designed and constructed so as to ensure that brittle crack does not initiate. Furthermore, in case a brittle crack should be initiated by chance, it is essential that a back-up brittle crack arresting function be included in the steel plates[2)]. Many studies have been conducted on the crack-arrestability of steels. It is reported that a brittle fracture test, performed on a model test body simulating a T joint for a hatch side coaming and upper deck, gave a result indicating that a steel plate having a thickness of 60mm can serve as an effective crack arrester if it has a K_{ca} value (brittle crack propagation-arrest toughness) no smaller than 6,000N/mm$^{1.5}$ at a test temperature of -10℃[3, 4)].

However, only a few reports refer to the methods for producing such a heavy thickness in steel plates for hull structures, i.e., a plate thicker than 50mm and having high arrestability with a K_{ca} value (-10℃) exceeding 6,000N/mm$^{1.5}$.

In this development work, heavy-thickness steel plates were control rolled under optimum conditions with stringent roll control in the temperature zones that respectively cause recrystallization and non-recrystallization. As a result, a technique was established for producing a steel plate with a high arrestability with a K_{ca} value (-10℃) exceeding 6,000N/mm$^{1.5}$. This paper outlines an overview of the production technique and introduces the characteristics of the newly developed steel plate.

1. Development target

Table 1 shows the target properties to be achieved by this development work. The target mechanical properties for the base metal and welding joint are to meet the requirements of the Nippon Kaiji Kyokai (NK) standard, KE36.

The arrest characteristics of the base metal aim to satisfy the minimum brittle crack-arrest toughness at the test temperature of -10℃, K_{ca} (-10℃), to be no lower than 6,000N/mm$^{1.5}$, according to the "Guidelines on Brittle Crack Arrest Design" proposed by Class NK[4)].

Table 1 Target properties

Grade	Thickness (mm)	Base metal properties				Arrestabilty	Properties of welded joints		
		YP (MPa)	TS (MPa)	EL (%)	vE_{-40} (J)	K_{ca}(−10℃) (N/mm$^{1.5}$)	Welding method	TS (MPa)	vE_{-20} (J)
KE36	60	≧355	490〜620	≧21	≧34(Ave.) ≧24(Each)	≧6,000	1pass EGW*	490〜620	≧34(Ave.) ≧24(Each)

*EGW (Electrogas welding)

2. Development concept

Improvement of arrest characteristics is known to be achieved by several techniques including: 1) refining the grain size of the surface layer to 1 - 3 μm [5]; and 2) balancing the grain refining and the deformation texture of ferrite [6].

This development work aims to establish a technique for producing a steel plate having arrestability with a K_{ca} value (-10 ℃) exceeding 6,000N/mm$^{1.5}$ by fully exploiting the capacity of the existing facilities.

As shown in **Fig. 1**, K_{ca} is reported to correlate with the toughness of a base metal at $t/4$ portion (fracture surface transition temperature *vTrs*)[7]. If there is no slip deformation, cracks in a steel material generally propagate along a crystal plane with a low surface energy before causing fracture[8]. Therefore, the toughness of the base metal can be effectively improved by increasing the grain boundaries having misorientation angles greater than 15 degrees. Such grain boundaries serve as resistance against brittle cracks [9]. Grain boundaries with misorientation angles greater than 15 degrees are here referred to as "high angle grain boundaries." It is important to refine grains surrounded by high angle boundaries to improve the toughness of the base metals, because such refinement is considered to result in the improvement of the arrest characteristics ($K_{ca} \geqq$ 6,000N/mm$^{1.5}$). In the case of heavy-thickness steel plates, however, the applicable rolling reduction is so limited and the temperature deviation in the thickness direction is so large that the conventional rolling technique will not allow rolling in the required temperature zones, making refinement difficult.

To resolve this issue, a technique called thermo mechanical control process (TMCP) was introduced. This technique enables an adequate control of the rolling reduction in the recrystallization and non-recrystallization temperature zones [10]. The technique was fine tuned for the rolling temperature regions and rolling reduction. More specifically, the conventional technique involves rolling continuously across the high temperature regions from the recrystallization temperature zone to non-recrystallization temperature zone. This conventional method is modified by incorporating steel plate cooling during the rolling to allow tighter temperature control. A study was conducted on the rolling in the low temperature region at a non-recrystallization temperature immediately above the Ar3 transformation point. The temperature is considered to facilitate grain refinement by effectively introducing strain (nucleation sites) to austenite grains.

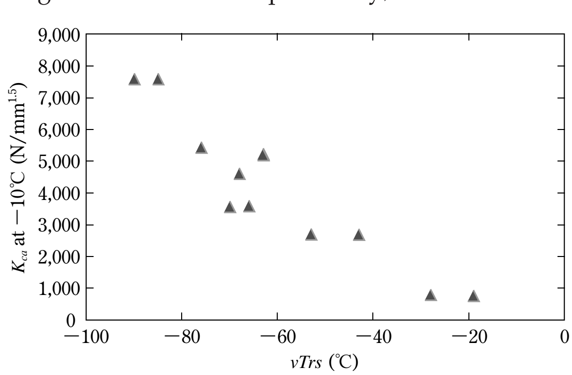


Fig. 1 Relationship between K_{ca} at −10℃ and *vTrs* ($t/4$)

3. Features of newly developed steel

3.1 Chemical composition and mechanical properties of base metal

The chemical composition of the newly developed steel is shown in **Table 2**. To ensure toughness at low temperatures in the heat affected zone (HAZ) caused by high heat input welding, the C content is limited to 0.08% in order to prevent the toughness deterioration caused by island-shaped martensite. For this purpose, C_{eq} is maintained as low as 0.34%. A small amount of Ti is added to prevent the toughness deterioration caused by the coarsening of prior austenite grain. Furthermore, a small amount of Nb, which expands the non-recrystallization temperature zone, is added in order to promote the refinement of the grains surrounded by high angle boundaries.

The relation between the size of grains surrounded by high angle boundaries and K_{ca} (-10℃) was studied under various TMCP conditions. The result is shown in **Fig. 2**. As predicted, K_{ca} is

Table 2 Chemical compositions of developed steel

(mass%)

	C	Si	Mn	Ti	Others	C_{eq}
Developed Steel	0.08	0.12	1.55	0.012	Nb, B, Ca	0.34

C_{eq}=C+Mn/6+(Cr+Mo+V)/5+(Cu+Ni)/15

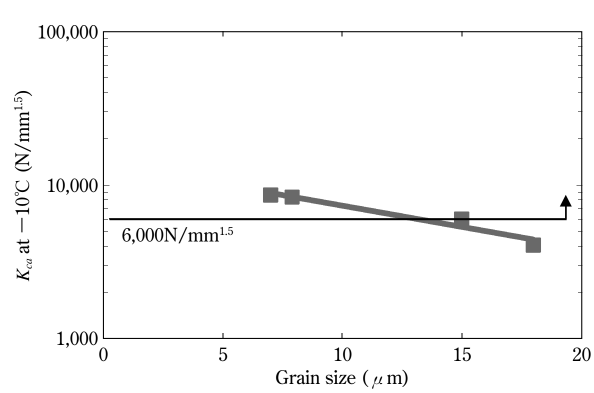


Fig. 2 Relationship between high angle grain size and K_{ca} at −10℃

improved by refining grains surrounded by high angle boundaries. By making these grains no larger than 10μm, the target of K_{ca} (-10℃)≧6,000N/mm$^{1.5}$ was achieved.

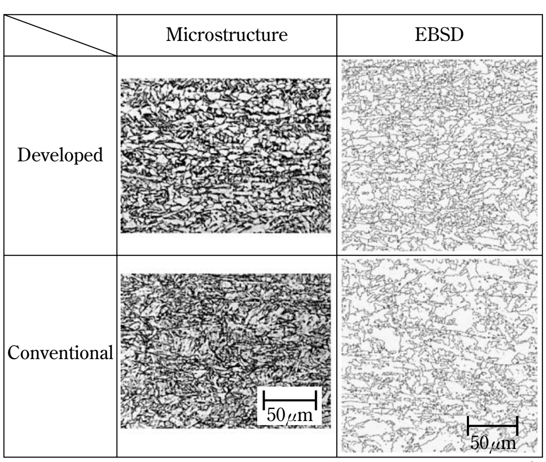
Now, a study was conducted to establish a production technique for decreasing the grain size to under 10μm while maintaining high angle boundaries to ensure arrest characteristics. **Fig. 3** shows micrographs and electron backscattering diffraction (EBSD) patterns mapping the crystal orientations at grain boundaries of newly developed and conventional steels[11]. The grains mapped are those surrounded by high angle boundaries with crystal misorientation greater than 15 degrees. The conventional steel has a structure mainly consisting of upper bainite. By introducing an adequate amount of strain in a low temperature range between the recrystallization temperature and non-recrystallization temperature, the newly developed steel is changed so as to have a structure mainly consisting of polygonal ferrite in which grains surrounded by high angle boundaries with crystal misorientation greater than 15 degrees are refined. This is attributable to the strain introduced at a low temperature between the recrystallization temperature and non-recrystallization temperature, which serves to form ferrite nuclei in the austenite grains and to promote the generation of polygonal ferrite[12].

Table 3 shows the base metal properties of the steel tested. The newly developed steel plate exhibits the mechanical properties that satisfy the target with vE_{-40}, greater than 340J, sufficiently exceeding the target value (34J). As shown in **Fig. 4**, the developed steel plate exhibits a favorable fracture surface transition temperature of lower than -90℃.

3.2 Brittle crack propagation-arrest characteristics

Brittle crack propagation-arrest characteristics were evaluated by K_{ca} values, calculated from the results obtained by an ESSO test[5] specified by the Guidelines on Brittle Crack Arrest Design. **Fig. 5** shows the result of the ESSO test. By extrapolating the fitted line, the developed steel is expected to have K_{ca} exceeding 8,000N/mm$^{1.5}$ at the lowest use temperature (-10℃), which sufficiently satisfies the minimum brittle crack arrest toughness value K_{ca} (-10℃)≧6,000N/mm$^{1.5}$ specified by the Guidelines on Brittle Crack Arrest Design.

Fig. 6 shows an example of the fracture surface,



※Position：t/4

Fig. 3 Microstructure and grain boundary map with EBSD

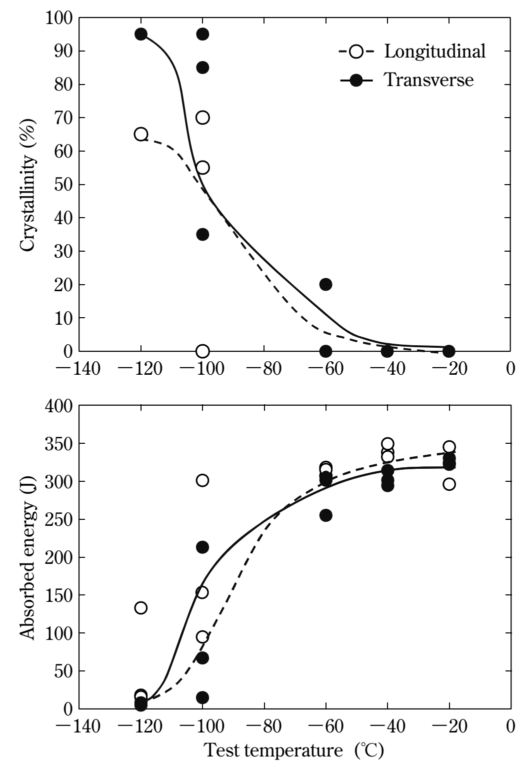


Fig. 4 Charpy transition curve of developed steel plate

Table 3 Mechanical properties of developed steels

	Thickness (mm)	Base metal properties				
		YP*1 (MPa)	TS*1 (MPa)	EL*1 (%)	vE_{-40} (J)*2	*vTrs* (℃)
Developed Steel	60	425	538	31	340 (Ave.) 338, 332, 349 (Each)	−100
Conventional Steel	60	499	615	23	231 (Ave.) 235, 230, 229 (Each)	−60
KE36 Target properties	60	≧355	490～620	≧21	≧34 (Ave.) ≧24 (Each)	－

*1 Round tensile specimen：NK14A　*2 Charpy test specimen：NKU4

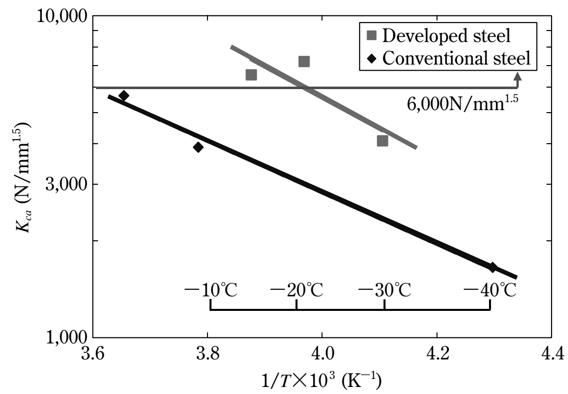


Fig. 5 Results of ESSO test

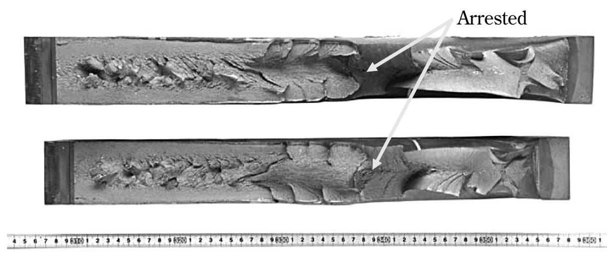


Fig. 6 Fracture surface of specimen after ESSO test

in which brittle crack is arrested as a result of toughness improvement associated with the temperature gradient. It is considered that, as a shear-lip extends from the surface layer to the interior ($t/8$ - $t/4$) of the steel plate, the driving force of brittle fracture becomes smaller than the kinetic fracture toughness value at the center of plate thickness. This serves to arrest the brittle crack[8]. The developed steel exhibits fracture surface having a shear-lip extending to $t/8$ - $t/4$. The plastic deformation at the shear-lip is considered to absorb energy for crack propagation, improving the arrest characteristics.

3.3 Characteristics of high-heat-input welding joint

High-heat-input welding is performed for assembling the hatch side coaming and upper deck of a container ship to assure high construction efficiency. To simulate the work done at these portions, electro-gas welding (EGW) with a single electrode was performed with high heat input. The welding conditions for the developed steel plate are shown in **Table 4** and the welding joint characteristics are shown in **Table 5**. The welding was performed with a high heat input of 450kJ/cm. The joint strength satisfies the target value. In addition, positive results were obtained regarding the joint toughness: a Charpy absorbed energy of 34J or more was achieved at all notch positions in the V-notch Charpy impact test at a test temperature of -20℃.

Table 4 Conditions of EGW

Thickness (mm)	Groove angle(°)	Root gap (mm)	Welding consumable	Number of passes	Welding current (A)	Welding voltage (V)	Welding speed (cm/min)	Heat input (kJ/cm)
60	20	8	Wire：DWS-1LG (ϕ1.6mm) Shielding gas：CO_2	1	400	43	2.3	449

Table 5 Mechanical properties of EGW welded joint

Thickness (mm)	Properties of welded joints					
	TS*1 (MPa)	Broken location	vE_{-20}min*2(J)			
			Position	Depo	Bond	Bond+1mm
60	583	HAZ	Surface $t/2$ Back	113 91 108	208 204 207	199 203 182
KE36 Target properties	490 ~620	–	≧34(Ave.) ≧24(Each)			

*1 Round tensile specimen：NKU2A　*2 Charpy test specimen：NKU4

Conclusions

An adequate amount of strain was introduced at a low temperature in the range between the recrystallization temperature and non-recrystallization temperature to produce a microstructure mainly consisting of fine polygonal ferrite. As a result, grains surrounded by high angle boundaries were successfully refined in a heavy- thickness steel plate having a thickness exceeding 50mm.

The results satisfy the minimum brittle crack arrest toughness value K_{ca} (-10 ℃)≧6,000N/mm$^{1.5}$ specified in the Guidelines on Brittle Crack Arrest Design. The developed steel responds to the need for larger and safer container vessels, which continue to be built. The demand for the newly developed steel is expected to grow rapidly.

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