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Brittle Crack Arrest Technique for Large Container Ships Using Fillet Welding

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Abstract:

The effect of fillet weld metal toughness and steel plate thickness on the long brittle crack arrest condition in a hatch side coaming of container ships was investigated. If a Tee joint composed of a hatch side coaming and a strength deck is constructed by fillet welding without a groove, long brittle cracks could be arrested in the fillet weld metal part by appropriately adjusting the fillet weld metal toughness according to the steel plate thickness. In addition, in the actual construction of the fillet Tee joint, even if a clearance (gap) was generated between the strength deck and the hatch side coaming, and an additional leg length was required, long brittle cracks could be arrested by optimizing the fillet weld metal toughness according to the fillet weld leg length.

1. Introduction

Accompanying the high level of activity in marine transport, the scale of ships has also become progressively larger in recent years. This trend toward larger ship size is particularly remarkable in container ships. Since the first 10 000 TEU class container ships appeared in 2005, ship size has increased rapidly, and ultra large container ships (ULCS) of 20 000 TEU class have been constructed recently (TEU: twenty foot equivalent unit, number of 20 foot containers that can be loaded on a ship). Because container ships are designed to secure hull strength by the strength deck and hatch side coaming, which are structural members of the superstructure, with consideration for the hull structure, extremely thick gauge high strength steel plates with thicknesses exceeding 50 mm are used in these members.

In heavy-thickness steel plates exceeding 50 mm, fracture toughness decreases due to the thickness effect, and the increased welding heat input also tends to accelerate a decrease in weld fracture toughness. In

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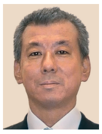

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welded joints of heavy-thickness steel plates, it has been shown experimentally that a brittle crack which initiates from the weld propagates linearly along the weld[1], and this had become an issue for application of heavy-thickness plates in ship hull structures.

Therefore, from the viewpoints of securing the integrity of the ship hull and preventing brittle fracture, the International Association of Classification Societies (IACS) requires structural measures such as butt shift and the application of designs which are capable of arresting crack propagation in the unlikely event that a brittle crack occurs, such as application of steel materials with excellent brittle crack arrestability (arrestability), defined as a brittle crack arrest toughness value (K_{ca}) of 6 000 N/mm$^{3/2}$ or more, in the strength deck and hatch side coaming[2, 3].

Tee joints consisting of the hatch side coaming and strength deck, in which heavy-thickness steel plates are used, are welded by fillet welding without a groove or by partial penetration welding. With the aim of arresting brittle cracks in Tee joints which are orthogonal to welded joints of heavy-thickness steel plates, in this research, we conducted large-scale model tests assuming that a brittle crack that propagates linearly in a weld runs into the Tee joint of a hatch side coaming and strength deck, and clarified the conditions for arrest of the brittle crack in the weld metal of the Tee joint in actual structures by investigating the propagation and arrest behaviors of brittle cracks in Tee joints.

2. Structural Arrest Technology

"Guidelines on Brittle Crack Arrest Design"[4] issued by Nippon Kaiji Kyokai (ClassNK) stipulates that a brittle crack arrest design which satisfies two scenarios (**Fig. 1**) should be considered: Scenario 1 is to prevent the propagation of a brittle crack that initiated in the hatch side coaming to the strength deck, and conversely, Scenario 2 is to prevent the propagation of a brittle crack that initiated in the strength deck to the hatch side coaming. Both scenarios assume that a butt-welded joint contains an initial defect, which is smaller than the allowable defect dimensions in nondestructive inspection of the weld, and suppose that this defect gradually develops due to the fluctuating longitudinal bending stress which occurs when a ship encounters waves, etc., and a brittle crack initiates with this defect as its point of origin and then propagates in the butt-welded joint.

Structural arrest design is a technique whereby a brittle crack is arrested by a structural discontinuity (unwelded face) which exists in a Tee joint of the hatch side coaming and strength deck, as shown in **Fig. 2**. It is thought that the brittle crack is arrested because the propagation path of the crack is physically limited by the structural discontinuity and the discontinuity releases the driving force of crack propagation, and this effect has been verified experimentally[5]. Fig. 2 shows the difference in arrestability depending on the width of the structural discontinuity. In a full penetration weld (Fig. 2, left), which does not contain a discontinuity, the brittle crack which propagated through the crack-running plate penetrates through the full thickness of the test plate, but on the contrary, in the partial penetration weld (Fig. 2, center), where the width of the discontinuity is wide, the brittle crack is arrested after running into the test plate. Moreover, in the fillet weld without a groove (Fig. 2, right), which had the widest discontinuity, it can be understood that the brittle crack is arrested without running into the test plate[5]. Similarly, this brittle crack arrest effect of a structural discontinuity has also been confirmed in a full-scale test simulating the hatch side coaming of a large container ship (**Fig. 3**)[6]. Here, it may be noted that the test plates which were penetrated by the running brittle crack in this test were general steel plates

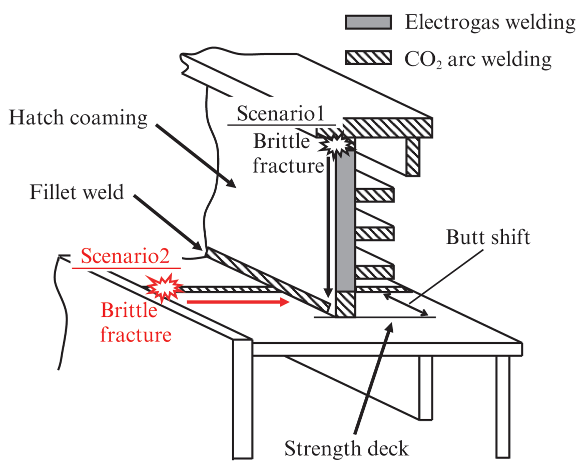


Fig. 1 Brittle crack propagation assumed in this research

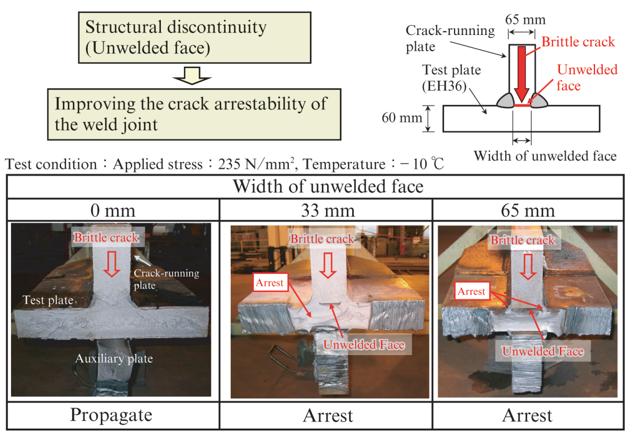


Fig. 2 Effect of structural discontinuity on brittle crack propagation/arrest behavior in Tee joint

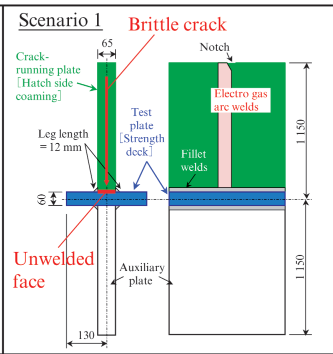
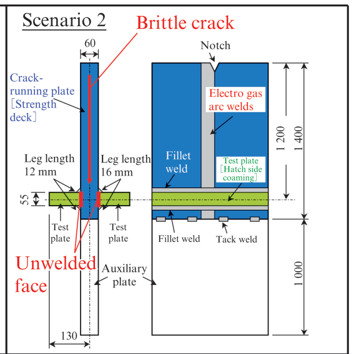
Specimen			
Width of root face	60 mm	55 mm	
Leg length	12 mm	12 mm	16 mm
Wire for welding	JIS Z 3313 T 49 4 T1-1 C A-U [φ1.2 mm]	JIS Z 3313 T 55 6 T1-1 C A-N3 [φ1.2 mm]	
Test temperature	−10℃		
Applied stress	283 N/mm^2		
Result	Arrest	Arrest	Arrest

Fig. 3 Results of ultra-large construction model tests

for ship structural use, and did not have guaranteed high arrestability of the base material. Based on this, it can be said that brittle cracks can also be arrested in the steel plates for ship structural use which are generally used in ships by appropriately controlling the width of the structural discontinuity (unwelded face) of the weld and the leg length of the fillet weld.

The technology described here for arresting the propagation of a brittle crack by strict control of the details of ship superstructure welds is called "structural arrestability." What is particularly important in this technology is the characteristics of the weld metal that are necessary to arrest a brittle crack when its propagation path is limited by a structural discontinuity. For instance, in the example in Fig. 3, the propagating brittle crack could be arrested in the fillet weld metal by fillet welding using a welding consumable for steels for low temperature service, which have extremely high low temperature toughness.

Focusing on the release of the brittle crack propagation driving force by the structural discontinuity in the Tee joint of a hull weld construction, it can be said that the structural arrestability technology is a rational design technique which makes it possible to arrest brittle cracks by using a welding consumable with appropriate low temperature toughness in combination with conventional steel plates[7].

3. Effect of Plate Thickness and Fillet Weld Metal Toughness on Propagation/Arrest Behavior of Long Brittle Crack Running into Tee Joint

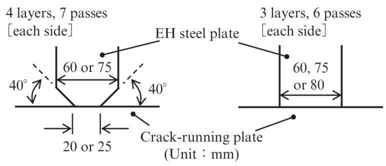
This chapter presents a detailed description of the results of an ultra-large construction model test of Tee joint structures with different plate thicknesses and weld metal toughness levels, which was carried out to clarify the effect of further increases in the toughness of the fillet weld metal and plate thickness necessary to arrest a long brittle crack by the structural arrestability technology.

As can be understood from Fig. 3, in comparison with Scenario 1, higher brittle crack arrestability is necessary in Scenario 2[8], in which a brittle crack that initiates and propagates in the butt joint of the strength deck is arrested by the hatch side coaming. Moreover, in the case of heavy-thickness steel plates, recent research[9] has also confirmed that higher brittle crack arrestability is necessary under Scenario 2 than under Scenario 1. Based on these points, this study was carried out for Scenario 2.

3.1 Experimental Method

The materials used as steel plates simulating the hatch side coaming were EH class heavy-thickness steel plates (thickness: 60 to 80 mm) for ship structural use. These plates were welded by fillet welding (leg length: 16 mm) without a groove on both sides of the welded joints (prepared by electro-gas arc welding) for initiation/propagation of brittle cracks. Samples were also prepared by partial penetration welding (leg length: 5 mm) for comparison purposes. **Table 1** shows the welding conditions. The toughness of the fillet welding weld metal was varied to three levels by changing the shield gas composition and type of welding wire. The weld metal toughness levels were confirmed by Charpy tests of butt-welded joints prepared under the same welding conditions. In addition to the welding wires with the three levels shown in Table 1, the high toughness fillet welding wire WMd (JIS Z 3313 T 55 6 T1–1

Table 1 Welding conditions of Tee joints

Tee joint	Partial penetration, Fillet welding		
Geometry of groove			
Leg length	Partial penetration: 5 mm, Fillet welding: 16 mm		
Welding method (Shielding gas)	GMAW (6-8%N_2+CO_2)	GMAW (100%CO_2)	GMAW (100%CO_2)
Wire for welding	WMa [ϕ 1.2 mm]	WMb [ϕ 1.2 mm]	WMc [ϕ 1.2 mm]
Preheating	130～150°C	None	None
Welding position	Horizontal /Flush fillet welding	Horizontal /Flush fillet welding	Horizontal /Flush fillet welding
Welding condition	300A-33V-34 cpm	300A-33V-30 cpm, 320A-34V-28 cpm	300A-33V-30 cpm, 320A-34V-28 cpm
vTrs*1 of weld metal	+4°C	-30°C	-62°C

*1: Charpy fracture appearance transition temperature obtained by toughness level survey tests using butt welding

Table 2 Test conditions and results of ultra-large construction model tests

Test temperature	-10°C						
Applied stress	257 N/mm^2						
Test No.	Crack-running plate thickness [UD] t_U (mm)	EH steel plate thickness [HSC] t_H (mm)	EH steel plate width W_H (mm)	A side: Tee joint / Wire for welding	A side: Arrest or propagate at WM	B side: Tee joint / Wire for welding	B side: Arrest or propagate at WM
Test 1	75	75	300	Partial / WMa	Propagate	Fillet / WMa	Propagate
Test 2	60	60	300	Fillet / WMc	Arrest	Fillet / WMb	Arrest
Test 3	75	75	300	Fillet / WMc	Arrest	Fillet / WMb	Propagate
Test 4	60	60	120	Fillet / WMa	Propagate	Fillet / WMb	Arrest
Test 5	75	80	115	Fillet / WMb	Propagate	Fillet / WMa	Propagate
Test 6	60	60	120	Fillet / WMa	Propagate	Partial / WMd	Propagate

C A-N3), which is applied to low temperature steels, was also used in one partial penetration welds for comparison, as shown in **Table 2**.

A total of six ultra-large construction model test specimens were prepared by changing the combinations of the plate thickness and the fillet welding weld toughness level. Table 2 and **Fig. 4** show the test conditions and the dimensions of the ultra-large construction model test specimens, respectively. The Tee joints arranged on the two sides of the welded joints (crack running plate) to facilitate brittle crack initiation and propagation are both objects of evaluation, and were prepared using different test conditions. However, the thickness and width of the EH class plates on the two sides were the same so as not to cause bending stress when tensile loading is applied. In the fillet welded Tee joint without a groove, the welding leg length was set

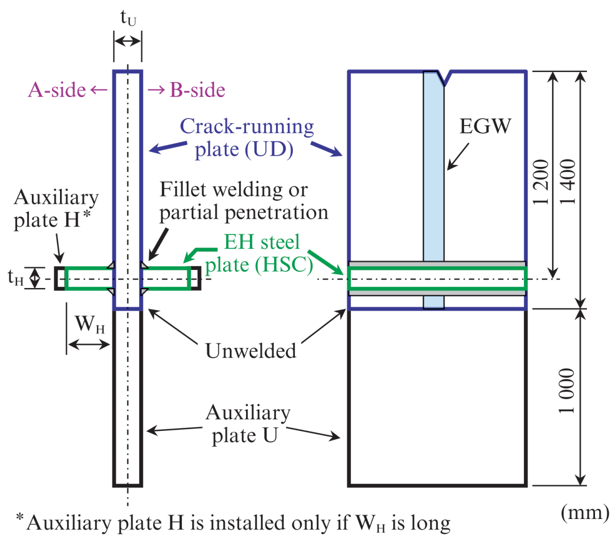


Fig. 4 Dimension of ultra-large construction model test specimens

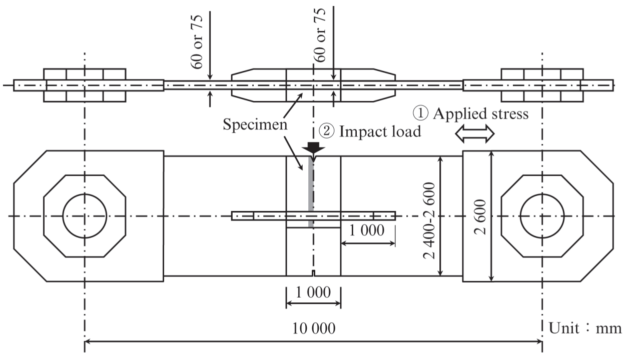


Fig. 5　Dimension of ultra-large construction model tests

to a constant 16 mm in order to observe the effects of the plate thickness and weld metal toughness level on brittle crack arrestability. The leg length of the partial penetration Tee joint prepared for comparison was 5 mm (standard value when a groove is used).

The test was conducted by cooling the specimen to −10°C and holding at that temperature for a minimum of 1 min/1 mm of plate thickness (= total of 60 to 80 min), applying a load equivalent to the maximum allowable stress (257 N/mm^2) of EH40 steel plates, and then striking the mechanical notch to cause brittle crack initiation and propagation. **Figure 5** shows the method of setting the test specimen on testing machine tab plate. The distance between the two pins (distance between load points) is 10 m.

3.2 Experimental Results

Table 2 shows the test results. In the partial penetration structure, the long brittle crack was not arrested even when the high toughness fillet welding wire was used (Table 2, Test 6, B side), but cases of crack arrest in the fillet weld metal were observed in the fillet welded structure without a groove. For example, in Test 3 with the 75 mm plate thickness, the long brittle crack was not arrested on the fillet weld metal side (B side) of vTrs = −30°C, but the crack was arrested on the fillet weld metal side of vTrs = −62°C. In Test 4 with the plate thickness of 60 mm shown in **Fig. 6**, the crack was not arrested on the fillet weld metal side of vTrs = +4°C, but arrest occurred on the fillet weld metal side of vTrs = −30°C. Although the crack was not arrested on the fillet weld metal side of vTrs = −30°C, a result showing arrest in the fillet weld metal at this vTrs was obtained with the 60 mm plate thickness.

Table 3 and **Fig. 7** summarize the results of the ultra-large construction model test for the fillet welded structure (leg length: 16 mm) without a groove. A tendency in which a long brittle crack is arrested more easily as the toughness of the fillet weld metal is better and as the plate thickness (thickness of plates simulating the strength deck) decreases can be observed.

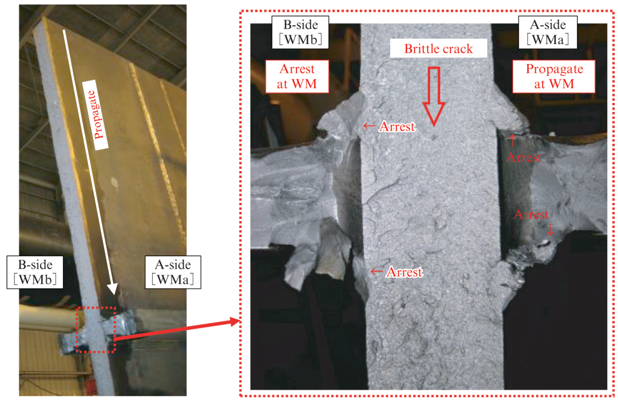


Fig. 6　Fracture surface of ultra-large construction model test specimen [Test 4 (HSC = 60 mmt, UD = 60 mmt)]

Table 3　Summary of the fillet weld metal toughness and ultra-large construction model test results in fillet Tee joint structure

Tee joint		Fillet welding (Leg length = 16 mm)		
Applied stress		257 N/mm^2		
Test temperature		-10°C		
Wire for welding		WMa	WMb	WMc
vTrs (°C)		+4	-30	-62
$vE_{-20°C}$ (J)		19	82	135
HSC = 60 mm	UD = 60 mm	Propagate	Arrest	−
HSC = 60 mm	UD = 60 mm	Propagate	Arrest	Arrest
HSC = 75 mm	UD = 75 mm	Propagate	Propagate	Arrest
HSC = 80 mm	UD = 75 mm	Propagate	Propagate	−

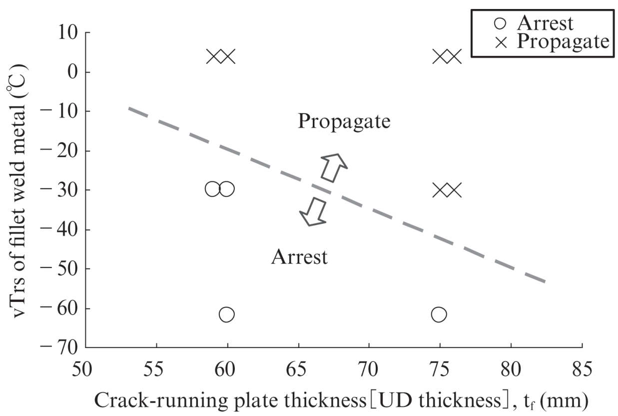


Fig. 7　Relationship between crack-running plate thickness and vTrs of fillet weld metal and long brittle crack propagation/arrest [leg length: 16 mm, applied stress: 257 N/mm^2, test temperature: −10°C]

In fillet welded structures (leg length: 16 mm) without a groove, it has also been confirmed that long brittle cracks can be arrested in the fillet weld metal portion by using an appropriate combination of the steel plate thickness and the fillet weld metal toughness level[10].

4. Effects of Fillet Weld Metal Toughness and Leg Length on Propagation/Arrest Behavior of Long Brittle Crack Running into Fillet Tee Joint

In actual welding of fillet Tee joints, a clearance (gap) may occur between the strength deck and the hatch side coaming, and it is sometimes necessary to increase the leg length. However, brittle crack arrest becomes more difficult because it is difficult to release the driving force of crack propagation if the leg length is increased. In order to clarify the fillet weld metal toughness level necessary for arrest of a long brittle crack when the fillet weld leg length is increased, an ultra-large construction model test was conducted with different fillet weld leg lengths and weld metal toughness levels in a Tee joint structure, and the conditions for arrest of a long brittle crack were investigated.

4.1 Experimental Method

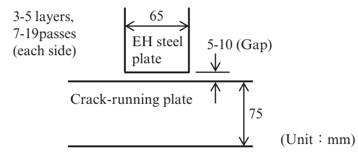
An EH class heavy-gauge steel plate (plate thickness: 65 mm) for ship structural use was used as the test plate simulating the hatch side coaming. A Tee joint was prepared by fillet-welding the test plate to a large heat input welded joint (electro-gas arc welded joint, plate thickness: 75 mm) in which a brittle crack was to be initiated/propagated. Based on the results described in the previous chapter, a fillet welded structure without a groove with satisfactory brittle crack arrestability was used as the Tee joint structure, and the leg length was changed to 19 mm, 21 mm or 24 mm (gap: 5 mm, 7.5 mm, 10 mm). **Table 4** shows the welding conditions. The toughness level of the fillet weld metal was changed by changing the welding wire used. The weld metal toughness of the fillet welds was confirmed by a Charpy test of butt-welded joints prepared under the equivalent welding conditions. The Charpy fracture appearance transition temperature vTrs of the weld metal of the welded joints was −38 to −41°C [WM1], −52 to −58°C [WM2] and −67 to −91°C [WM3] with welding heat input in the range of 10 to 20 kJ/cm. The vTrs of WM4 was lower than −80°C under the heat input condition of 10 kJ/cm.

A total of 3 ultra-large construction model test specimens (total of 6 conditions) were prepared by changing the combinations of the fillet weld leg length and the fillet welding wire and performing welding in the above-mentioned heat input range. **Table 5** shows the test conditions. The tests were conducted by applying a load equivalent to the maximum allowable stress (243 N/mm^2) of the EH36 steel plate by the same procedure as in section 3.1.

4.2 Experimental Results

Table 6 shows the test results, and **Fig. 8** shows an example of the appearance of the crack penetration area of the specimen and the fracture surface. Cases in which the long brittle crack was arrested in the fillet weld metal were also confirmed when the fillet weld leg

Table 4 Welding conditions of Tee joints with gap

Tee joint	Fillet welding						
Geometry of groove							
Target leg length (Gap)	19, 21, 24 mm (5, 7.5, 10 mm)						
Welding method	GMAW (Shielding gas: 100%CO_2)						
Welding position	Horizontal fillet welding						
Welding condition	200-290A, 27-32V, 21-68 cpm						
Wire for welding	WM1 (ϕ 1.2 mm)		WM2 (ϕ 1.2 mm)		WM3 (ϕ 1.2 mm)		WM4 (ϕ 1.2 mm)
Heat input*1 (kJ/cm)	20	10	20	10	20	10	10
vTrs*1 of weld metal (°C)	-38	-41	-52	-58	-67	-91	< -80

* 1: Toughness level survey test results using butt welding

Table 5 Test conditions of ultra-large construction model tests

Test temperature	-10°C						
Applied stress	243 N/mm^2						
Test No.	Crack-running plate thickness [UD] t_U (mm)	EH steel plate thickness [HSC] t_H (mm)	EH steel plate width W_H (mm)	Tee joint [Fillet weld structure]			
				A side		B side	
				Target leg length [Gap] (mm)	Wire for welding	Target leg length [Gap] (mm)	Wire for welding
Test 7	75	65	122	19 [5]	WM1	19 [5]	WM3
Test 8	75	65	122	24 [10]	WM1	24 [10]	WM2
Test 9	75	65	122	21.5 [7.5]	WM3	24 [10]	WM4

Table 6 Summary of ultra-large structural model test results in fillet Tee joint structure with gap

Tee joint	Fillet welding (HSC = 65 mm, UD = 75 mm)			
Applied stress	243 N/mm^2			
Test temperature	-10˚C			
Wire for welding	WM1	WM2	WM3	WM4
vTrs (˚C)	-38∼-41	-52∼-58	-67∼-91	<-80
Target leg length = 19 mm (Actual leg length = 19.5-20.0 mm)	Arrest [Test 7]	–	Arrest [Test 7]	–
Target leg length = 21.5 mm (Actual leg length = 23.0 mm)	–	–	Arrest [Test 9]	–
Target leg length = 24 mm (Actual leg length = 24.5-26.0 mm)	Propagate [Test 8]	Propagate [Test 8]	–	Arrest [Test 9]

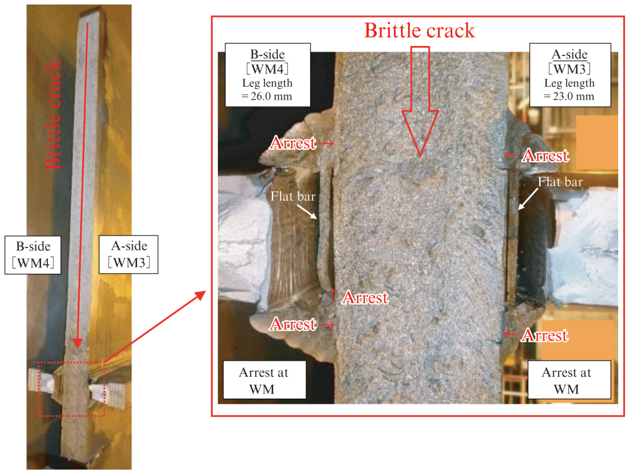


Fig. 8 Fracture surface of ultra-large construction model test specimen [Test 9]

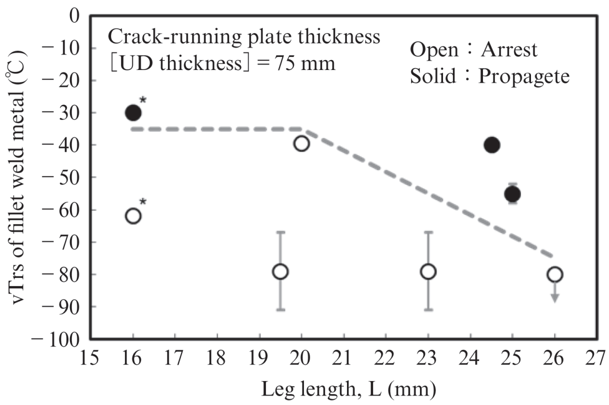


Fig. 9 Relationship between leg length and vTrs of fillet weld metal and long brittle crack propagation/arrest [UD thickness: 75 mm, applied stress: 243 N/mm^2 (*: 257 N/mm^2), test temperature: −10˚C]

length exceeded 16 mm. For example, in Test 8 with the 24 mm target leg length, the long brittle crack was not arrested in the fillet weld metal [WM2] of vTrs = −52 to −58˚C, but in Test 1 with the target leg length of 19 mm, the long brittle crack was arrested even in the fillet weld metal [WM1] of vTrs = −38 to −41˚C. Moreover, in Test 9 with the target leg lengths of 21.5 mm and 24 mm shown in Fig. 8, the long brittle crack could be arrested in the fillet weld metal [WM3] of vTrs = −67 to −91˚C and the fillet weld metal [WM4] of vTrs < −80˚C.

Figure 9 presents a summary of the results of the ultra-large construction model test of the fillet welds without a groove having fillet weld leg lengths exceeding 16 mm. Fig. 9 also shows the results for the fillet weld leg length of 16 mm in section 3.1. A tendency in which the long brittle crack is arrested more easily as the toughness of fillet weld metal is better and as the fillet weld leg length decreases can be observed.

In fillet weld structures without a groove, even when the leg length exceeded 16 mm, it has been confirmed that a long brittle crack can be arrested in the fillet weld metal by adjusting the toughness level of the fillet weld metal appropriately, corresponding to the fillet weld leg length [11].

5. Conclusion

Ultra-large construction model tests with dimensions approximating the size of the actual structure were conducted for long brittle cracks penetrating the hatch side coaming of fillet welded Tee joint structures with a structural discontinuity (unwelded face), and the effects of the steel plate thickness and the fillet weld metal toughness level and leg length (gap) on the conditions for long brittle crack arrest were investigated. The knowledge obtained in this study is summarized below.

(1) In the partial penetration welding structure (plate thickness: 60 mm, leg length: 5 mm, discontinuity width: t/3), the long brittle crack did not arrest even when a high toughness welding material (JIS Z 3313 T 55 6 T1–1 C A-N3) was applied.

(2) Cases in which the long brittle crack was arrested in the fillet weld metal were observed with the fillet welded structure without a groove (plate thickness:

60 to 80 mm, leg length: 16 mm), and the long brittle crack arrested more easily as the toughness of the fillet weld metal was better and as the plate thickness (thickness of the strength deck) decreased.

(3) It is possible to arrest long brittle cracks in the fillet weld metal by optimizing the weld leg length, the toughness level of the fillet weld metal and the thickness of the steel plate.

(4) With the fillet weld structure without a groove (strength deck thickness: 75 mm, hatch side coaming thickness: 65 mm), cases in which the long brittle crack arrested in the fillet weld metal were also observed when the leg length exceeded 16 mm, and the long brittle crack arrested more easily as the toughness of fillet weld metal was better and as the fillet weld leg length decreased.

(5) In welding of actual fillet weld Tee joints, a clearance (gap) may occur between the strength deck and the hatch side coaming, but even in cases where it is necessary to increase the leg length, it is possible to arrest a long brittle crack in the fillet weld metal by appropriately adjusting the fillet weld metal toughness level according to the fillet weld leg length.

References

1) Yamaguchi, Y.; Kitada, H.; Yajima, H. KANRIN. 2005, no. 3, p. 70–76.
2) IACS. “Requirements for Use of Extremely Thick Steel Plates in Container Ships”, UR S33, 2013–01, 2015–09 Rev. 1, 2019–12 Rev. 2.
3) IACS. “YP47 Steels and Brittle Crack Arrest Steels”, UR W31, 2013–01, 2015–09 Rev. 1, 2019–12 Rev. 2.
4) “Guidelines on Brittle Crack Arrest Design. ” Nippon Kaiji Kyokai. 2009.
5) Kiji, N.; Nakanishi, Y.; Toyoda, M.; Yokura, T.; Handa, T.; Suzuki, S. Brittle crack arrestability of T joint structure of thick plate. Preprints of the National Meeting of JWS. 2006, no. 79, p. 164–165.
6) Handa, T.; Igi, S.; Kiji, N.; Toyoda, M.; Takeda, H.; Inose, K.; Endo, S.; Shiomi, H. Long brittle crack arrest behavior in fillet Tee joint. Conference proceedings, the Japan Society of Naval Architects and Ocean Engineers. 2011, no. 13, p. 61–64.
7) Toyoda, M.; Handa, T. Structural Brittle Crack Arrest Design for Ultra Large Container Ship. Journal of the Japan Welding Society. 2012, vol. 81, no. 6, p. 485–488.
8) The 169th Research Committee of the Shipbuilding Research Association of Japan. 1979, no. 315, p. 118–136.
9) Kubo, A.; Yajima, H.; Aihara, S.; Yoshinari, H.; Hirota, K.; Toyoda, M.; Kiyosue, T.; Inoue, T.; Handa, T.; Kawabata, T.; Tani, T.; Yamaguchi, Y. Experimental study on brittle crack propagation behavior with large scale structural component model tests -Brittle crack arrest design for large container ships -5-. ISOPE-2012, 36–43.
10) Handa, T.; Toyoda, M.; Kiji, N.; Inose, K.; Watanabe, S.; Shiomi, H.; Igi, S.; Oi, K. Effect of fillet weld metal toughness on long brittle crack arrest behavior in Tee joint. Conference proceedings, the Japan Society of Naval Architects and Ocean Engineers. 2014, no. 19, p. 459–462.
11) Handa, T.; Toyoda, M.; Kiji, N.; Ikeda, R. Effect of Fillet Weld Metal Toughness and Leg Length on Long Brittle Crack Arrest Behavior in Tee Joint. Conference proceedings, the Japan Society of Naval Architects and Ocean Engineers. 2018, no. 26, p. 291–294.