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BRIEF NOTE

Effect of specimen size, applied stress and temperature gradient on brittle crack arrest toughness test

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Abstract Temperature gradient type ESSO test is one of the most popular test methods for evaluating the brittle crack arrest toughness, K_{ca}. However, test conditions which are specimen shape, tab plate shape, applied stress and temperature gradient affect K_{ca}. This document reports effects of specimen geometries that are specimen width, tab plate length, tab plate thickness and tab plate width on K_{ca} evaluation. In addition, effects of applied stress and temperature gradient have also been investigated. Temperature gradient type ESSO tests are conducted at three different steel mills in Japan. Then, test conditions were varied and test results were compared. In the result, influence range of effect specimen width, tab plate thickness, applied stress and temperature gradient were demonstrated. The applicable range of specimen geometry, applied stress and temperature gradient were clarified and implemented to the brittle crack arrest standard.

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Keywords Brittle fracture · Crack arrest toughness · K_{ca} · Specimen geometry · Applied stress · Temperature gradient

1 Introduction

Fracture control design is often applied for steel structures, such as cryogenic storage tanks, penstocks, etc. Brittle crack initiation is needed to prevent in those structures in principal. However, it is difficult to control the brittle fracture initiation on large scale steel structures completely even suitable fracture control design is applied because of various unexpected causes. Brittle crack arrestability of structural steels is essentially important for the integrity of large steel structures to prevent fatal accidents for some large structures whose damage may cause significant social loss. This double integrity concept which prevents both initiation and propagation of brittle fracture can decrease risk by brittle fracture dramatically.

However, there is no strictly described standard of brittle crack arrest toughness test of full thickness steel plate until Class NK published the standard K_{ca} test method which is temperature gradient type ESSO test (Class 2009). Temperature gradient type ESSO test is one of the most popular test methods for evaluating the brittle crack arrest toughness. However, the effects of test conditions are not always clearly investigated even standard K_{ca} test method of Class NK.

In this research, effect of the test specimen size, tab plate size, applied stress and temperature gradient were investigated. Additionally, validity range of test condition was introduced.

2 Effect of specimen width

2.1 Case of narrow width specimen

2.1.1 Testing conditions

Temperature gradient type ESSO tests are conducted for three kinds of specimen width. To investigate the narrow width, specimen width is even or less than 500 mm which is standard specimen width. Chemical compositions and mechanical properties of the steel used are shown in Tables 1 and 2.

Testing system is shown in Fig. 1. Test specimen width and other testing conditions are shown in Table 3.

2.1.2 Results

Test results described in Table 3 and Fig. 2 compares the Arrhenius plots of K_{ca} obtained from test specimens with a narrow width to those obtained from standard width. In the low temperature side where K_{ca} decreases, the values of K_{ca} obtained from test specimens with the width of 350–400 mm are slightly lower than those obtained from standard test specimens with the width of 500 mm.

2.1.3 Discussion

The reason of K_{ca} decreases at narrow width is that impact energy which is applied for initiating brittle crack increases the dynamic stress intensity factor, K_d, in a short crack length (The Japan Welding Engineering Society 2014).

Considering that the results obtained from test specimens with a narrow width are on the safe side, and also considering the practicality of testing, the use of narrow width specimens is allowed. Since, however, too narrow test specimens are likely to give too low values of K_{ca}, the lower limit of test specimen width is specified as 350 mm.

Table 1 Chemical compositions [mass%]

Thickness (mm)	C	Si	Mn	P	S
30	0.10	0.17	1.45	0.008	0.002

Table 2 Mechanical properties

Thickness (mm)	YP (N/mm^2)	TS (N/mm^2)	vTrs (°C)
30	368	471	−89

2.2 Case of wide width specimen

2.2.1 Testing conditions

Temperature gradient type ESSO tests are conducted for three kinds of specimen width. To investigate the wide width, specimen width is even or more than 500 mm which is standard specimen width. Chemical compositions and mechanical properties of the steel used are shown in Tables 4 and 5.

Figure 3 shows the testing system. Test specimen width and other testing conditions are shown in Table 6.

2.2.2 Results

Table 6 shows the test results and Fig. 4 shows the results comparing the values of arrest toughness obtained from test specimens with a width of 500–1000 mm made from the same material. The values of K_{ca} obtained from wide test specimens with the width of 700–1000 mm are almost the same as those obtained from standard width specimen.

2.2.3 Discussion

Case of using wide width specimen larger than 1000 mm, distance between loading pins shorter than 4 m has possibility to decrease K_d by stress reflection (The Japan Welding Engineering Society 2014). In addition, considering the practicality of testing, acceptable distance between loading pins is 4 m or less.

Considering that test specimens with a width up to at least 1000 mm have little effect on K_{ca} values, the upper limit of test specimen widths is specified as 1000 mm.

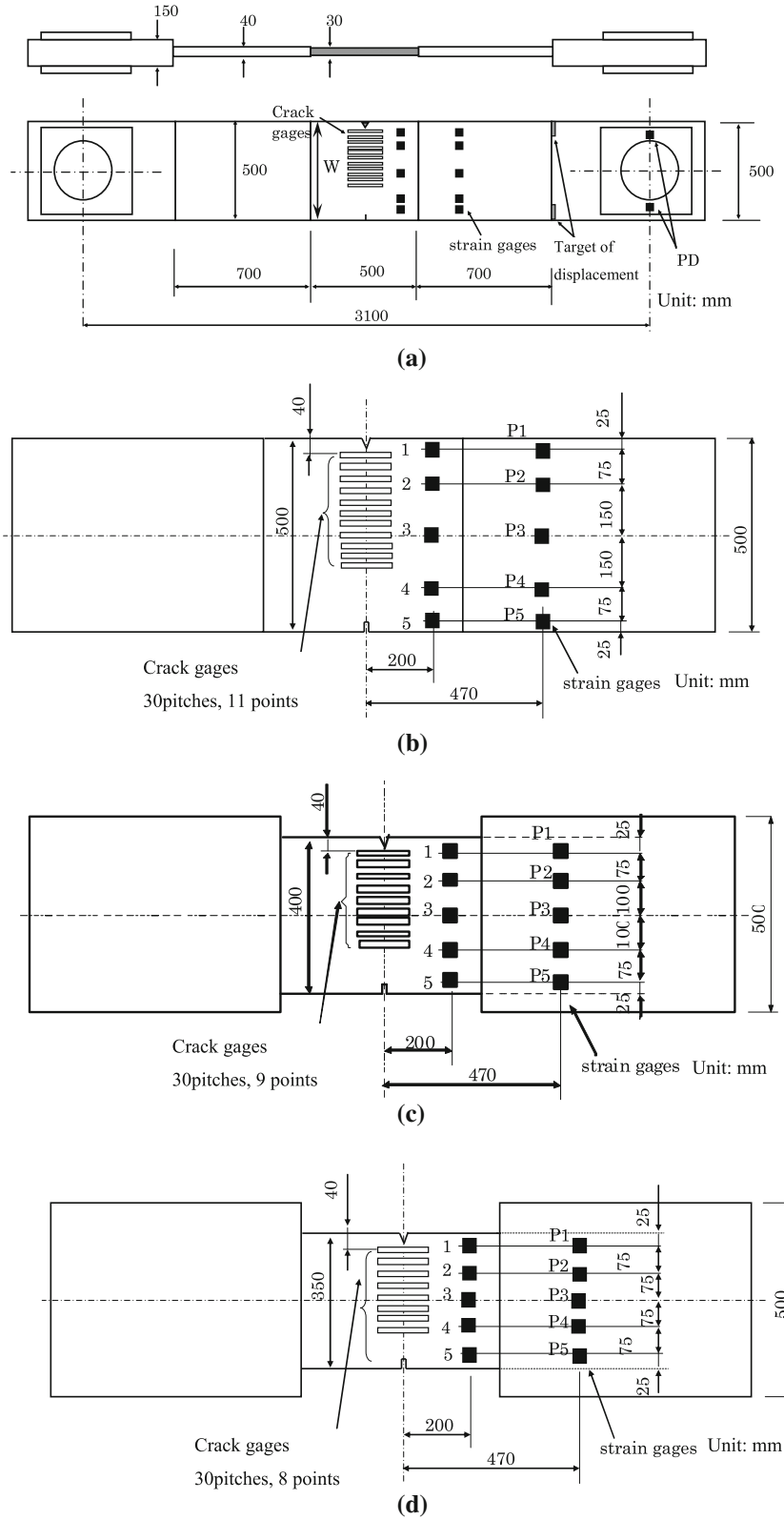


Fig. 1 Dimension of narrow width specimen. **a** Dimension of specimen and general dynamic measurement. **b** Specimen configuration and position of each gage on W = 500 mm. **c** Specimen configuration and position of each gage on W = 400 mm. **d** Specimen configuration and position of each gage on W = 350 mm

Table 3 Testing conditions and results on case of narrow width specimen

Width (mm)	Applied stress (N/mm^2)	Temperature at the crack arrest position (°C)	Arrest crack length (mm)	Arrest toughness value (N/mm$^{3/2}$)
500	335.3	−18.6	335.3	3892
	297.5	0.4	297.5	6870
	257.2	−7.5	257.2	5252
400	137	−6.1	247.2	4666
	104	−12.2	242.7	3492
	245	−1.4	186.6	6573
350	190	0.3	220.8	6203
	109	−18.9	160.3	2704
	147	−16.4	158.5	3621

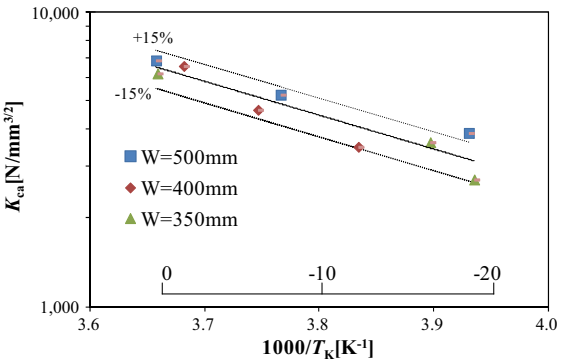


Fig. 2 Effect of the narrow specimen width on the results of arrest toughness tests

Table 4 Chemical compositions [mass%]

Thickness (mm)	C	Si	Mn	P	S
80	0.14	0.40	1.42	0.016	0.003

Table 5 Mechanical properties

Thickness (mm)	YP (N/mm^2)	TS (N/mm^2)	vTrs (°C)
80	355	518	−65

3 Effect of tab plates dimension

3.1 Various kind size of tab plate

3.1.1 Testing conditions

To verify the effect of tab plate size, various kind size of tab plate is used for temperature gradient type ESSO tests. 16 mm thick steel plate is used for specimen and the standard tab plate thickness is same thickness of test specimen. Chemical compositions and mechanical properties of the steel are shown in Tables 7 and 8.

Testing system is shown in Fig. 5. Tab plate size and other testing conditions are shown in Table 9.

3.1.2 Results

Table 10 shows the test results and Fig. 6 shows the results of comparing the values of K_{ca} in various kind of tab size. In a range of tab plate thickness up to 1.5 times the test specimen thickness, the values of K_{ca} are almost the same independently of the tab plate thickness. On the other hand, in case of using wide width tab plate up to 2.0 times the test specimen width, the values of K_{ca} are almost the same that of 1.0 times the test specimen width. In addition, in a range of tab plate length up to 3.0 times the test specimen length, K_{ca} values are roughly in a line giving a linear Arrhenius plot of 1.0 times the test specimen length.

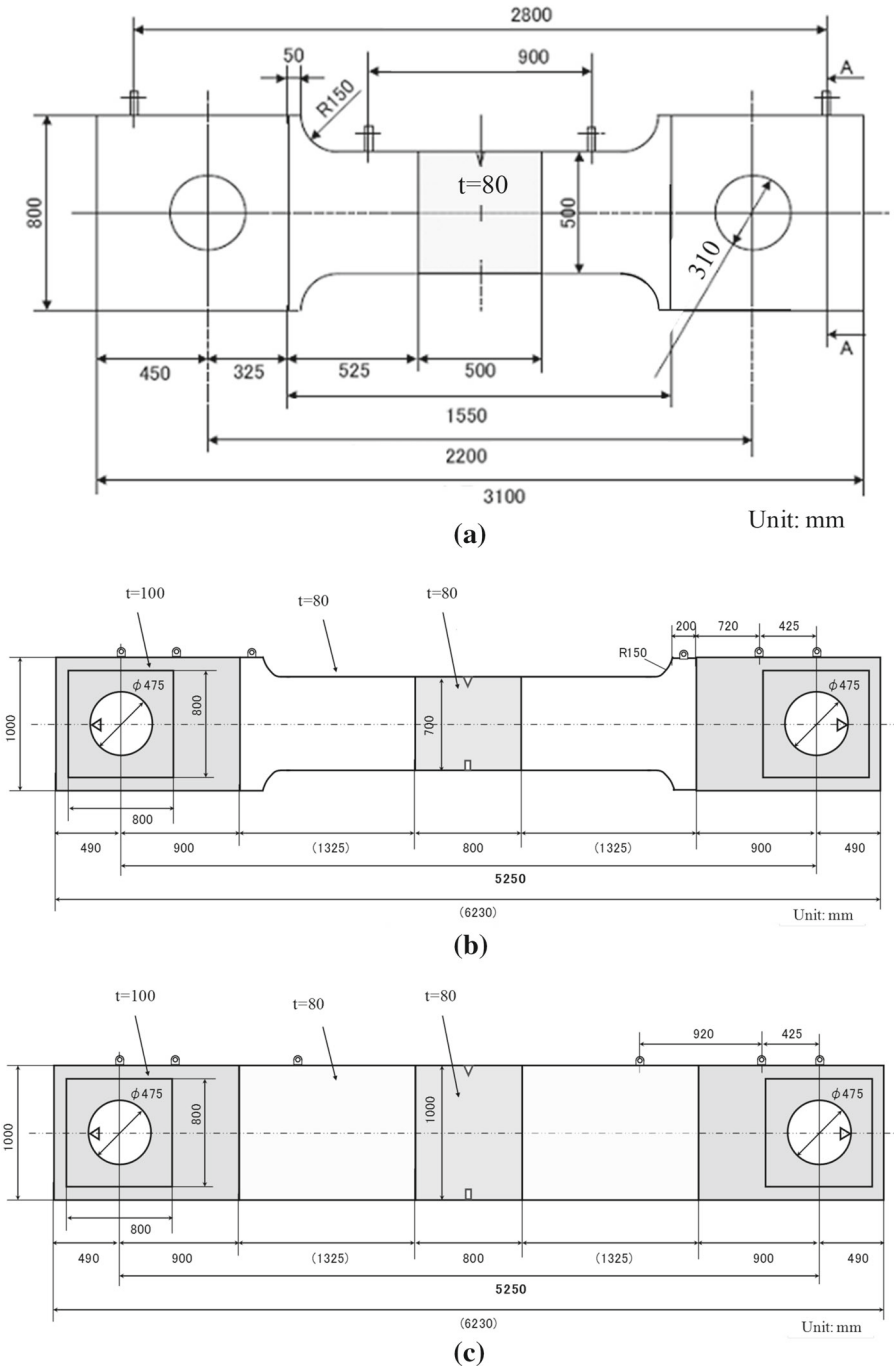


Fig. 3 Dimension of wide width specimen. **a** Specimen configuration on W = 500 mm. **b** Specimen configuration on W = 700 mm. **c** Specimen configuration on W = 1000 mm

3.1.3 Discussion

In the case of thicker tab plate than test specimen, stress reflection at the boundary between specimen and tab plate affects on decrease of stress around crack tip (Kawabata et al. 2010).

As a result, the upper limit of tab plate thickness as 1.5 times the test specimen thickness is recommended.

Figure 6 also shows the measurement results of K_{ca} in the case of widening the tab plate width to 2.0 times the test specimen width. The results indicate that, in the case of tab plate widths in a range of 1.0–2.0 times the

Table 6 Testing conditions and results on case of wide width specimen

Width (mm)	Applied stress (N/mm^2)	Temperature at the crack arrest position (°C)	Arrest crack length (mm)	Arrest toughness value ($N/mm^{3/2}$)
500	87.9	−11.2	308	3348
	175.5	6.3	251	5567
	177.3	7.8	285	6265
700	176.9	12.1	400	7413
	142.1	6.3	378	5663
1000	141.7	6.5	526	6602

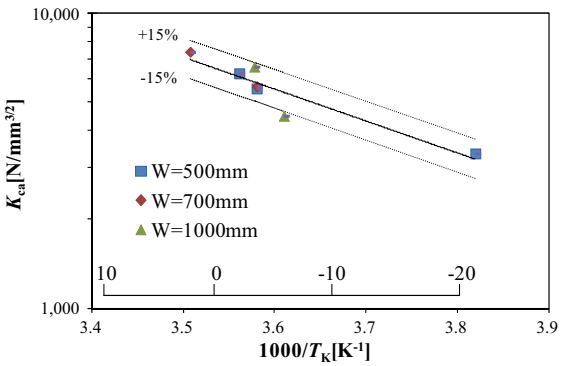


Fig. 4 Effect of the wide specimen width on the results of arrest toughness tests

Table 7 Chemical compositions [mass%]

Thickness (mm)	C	Si	Mn	P	S
16	0.06	0.13	1.37	0.006	0.0016

Table 8 Mechanical properties

Thickness (mm)	YP (N/mm^2)	TS (N/mm^2)	vTrs (°C)
16	321	448	-91

test specimen width, the tab plate width has no effect on the measured values of K_{ca}. As a result, tab plate widths as 1.0–2.0 times the test specimen width are allowed.

Additionally, Fig. 6 shows the results of K_{ca} measurement for different tab plate lengths. The values of K_{ca} obtained using the same length as the test specimen width (500 mm) are roughly the same as those obtained using a long tab plate with a length 3.0 times the test specimen width (1500 mm) with a small load drop. From these results, tab plate lengths are determined considering that the valid values of K_{ca} can be measured with a small load drop when the tab plate length is equal to or larger than the test specimen width. The total length of the test specimen and the tab plates shall be larger than 3.0 times the test specimen width.

Pin chuck shapes are not specified in detail. Pin chucks have to have enough strength to hold applied loads. In principle, however, pin chuck widths are specified to be equal to or larger than the tab plate width so that stresses are uniformly transferred to the test specimen and the tab plates.

3.2 Case of thin tab plate

3.2.1 Testing conditions

In order to investigate the effect of thin tab plate, two kinds thickness of tab plate are used for an ESSO tests. 50mm thick steel plate is used for specimen. Chemical compositions and mechanical properties of the steel are shown in Tables 11 and 12.

Testing system is shown in Fig. 7. Tab plate thickness and other testing conditions are shown in Table 13.

3.2.2 Results

Table 14 shows the test results and Fig. 8 shows the values of K_{ca} obtained from thin tab plate specimen. For comparison, Fig. 8 also shows the values of K_{ca} obtained from thick tab plate specimen. The results indicate that the values of K_{ca} decrease when using thin tab plates.

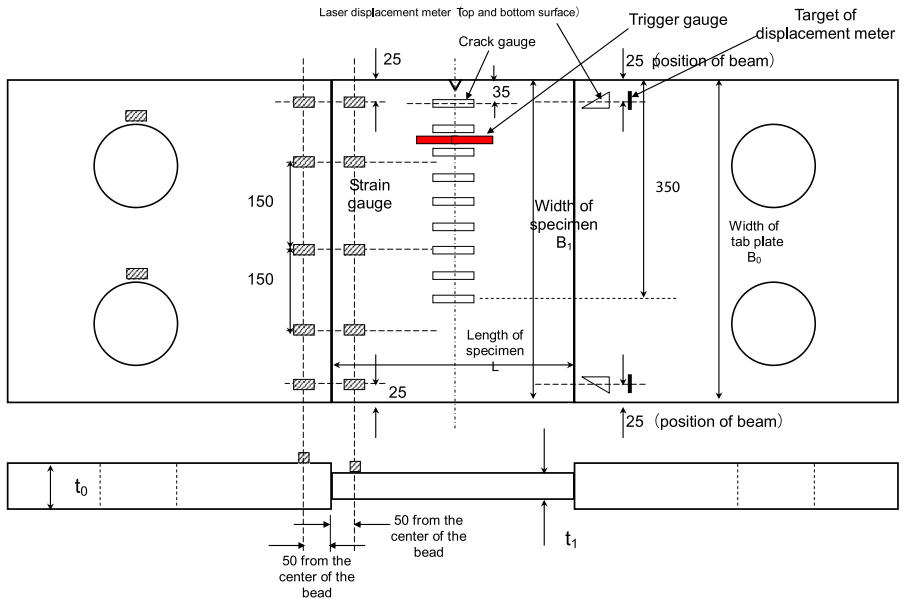


Fig. 5 Dimension of specimen and general of dynamic measurement on case of thick tab plate

Table 9 Testing condition on case of thick tab plate

Mark	Distance between pins (mm)	Tab plate thickness (mm)	Tab plate width (mm)	t_{tb}/t
S2	1500	16	500	1.0
S3				
S4	3500			
S5				
S6				
S7	1500	24		1.5
S8				
S9		50		3.1
S10				
S11		24	1000	1.5
S12				

3.2.3 Discussion

The reason K_{ca} decreases at thin tab plate that stress waves reflect to the tension side and act on the crack propagation area of the test specimen. As a result, lower K_{ca} values are estimated when using thin tab plates. Since the evaluation gives the results on the safe side, the use of thin tab plates is allowed considering the practicality of testing. However, too thin tab plates are likely to give too low values of K_{ca}, the lower limit of tab plate thickness is specified as 0.8 times the test specimen thickness.

4 Effect of applied stress

4.1 Testing conditions

To verify the effect of applied stress, lots of temperature gradient type ESSO tests are conducted using high strength steel with a specified minimum yield stress of 320–460 N/mm^2. Chemical compositions and mechanical properties of each steels used are shown in Tables 15 and 16. Width of all specimens is 500 mm.

Testing system is shown in Fig. 9. That of temperature gradient type ESSO test on Y32N80 steel is same as Fig. 3a. Test conditions are shown in Table 17.

4.2 Results

Table 17 shows the test results. The numbers which are described in the parentheses nearby plots in Fig. 10 show the ratios of applied stress to yield stress at room temperature. In the case of Fig. 10a, b, where all tests were conducted under the condition of an applied stress ratio of 0.5 or less, the data points are in a line giving a linear Arrhenius plot. On the other hand, in the case of Fig. 10c, the data points for an applied stress ratio of 0.673 were plotted higher than other data. Similarly in the cases of Fig. 10d, e, the data points for high applied stress ratios were plotted higher than other data.

Table 10 Testing results on case of thick tab plate

Mark	Applied stress (N/mm^2)	Temperature at the crack arrest position (°C)	Arrest crack length (mm)	Arrest toughness value (N/mm$^{3/2}$)
S2	100	−25	277	3444
S3	170	−5.7	301	6328
S4	130	−13.5	327	5291
S5	100	−17	305	3772
S6	160	−11	292	5782
S7	100	−20	295	3650
S8	170	−14	224	4952
S9	170	−20	236	5144
S10	100	−28	281	3488
S11	100	−23	275	3037
S12	170	−14	248	4871

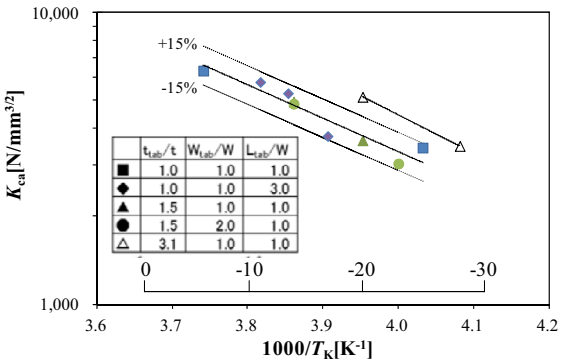


Fig. 6 Effect of the tab plate shapes on the results of arrest toughness tests (case of thick tab plate, wide tab plate and long tab plate)

Table 11 Chemical compositions [mass%]

Thickness (mm)	C	Si	Mn	P	S
50	0.13	0.40	1.43	0.014	0.003

Table 12 Mechanical properties

Thickness (mm)	YP (N/mm^2)	TS (N/mm^2)	vTrs (°C)
50	364	514	−69

4.3 Discussion

Increasing applied stress may increases the plastic zone a head of crack tip and leads to the decrease in crack driving force (Aihara et al. 2012). As a consequence, the K_{ca} for high applied stress ratios are plotted higher than other data.

From the above results, the applied stress as 2/3 or less of the yield stress at room temperature is recommended. Applied stresses higher than the above are likely to give higher values of K_{ca}. For information, this condition was obtained from the test results on high strength steel with a yield stress of 320–360 N/mm^2 and a thickness of 30–80 mm. Since the appropriate range of applied stresses may depend on yield stresses and thicknesses, further study is needed.

5 Effect of temperature gradient

5.1 Testing conditions

Difference in temperature gradient affects formation of side ligaments of the arrest test specimen. Therefore arrest test results may affected by temperature gradient. In this chapter, the effect of temperature gradient is investigated.

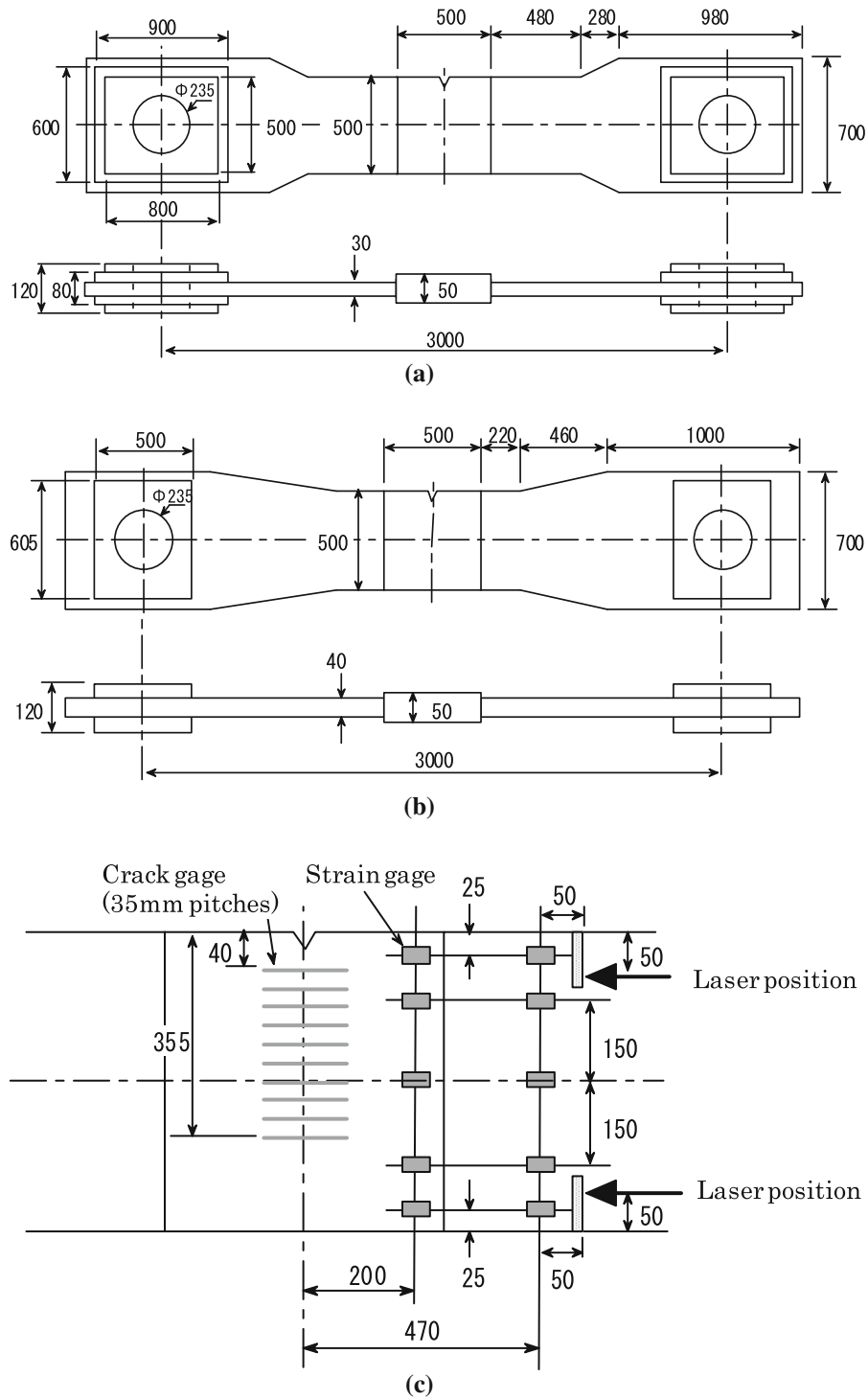


Fig. 7 Dimension of specimen and general of dynamic measurement on case of thin tab plate. **a** Dimension of specimen on 30 mm tab plate thickness. **b** Dimension of specimen on 40 mm tab plate thickness. **c** Position of each gages

Table 13 Testing condition on case of thin tab plate

Mark	Distance between pins (mm)	Tab plate thickness (mm)	t_{tb}/t
30-1	3000	30	0.6
30-2			
40-1		40	0.8
40-2			
40-3			

Table 14 Testing results on case of thin tab plate

Mark	Applied stress (N/mm^2)	Temperature at the crack arrest position (°C)	Arrest crack length (mm)	Arrest toughness value ($N/mm^{3/2}$)
30-1	147	6	305	5541
30-2	98	−9	295	3579
40-1	147	2	300	5468
40-2	98	−12	273	3336
40-3	196	7	241	6035

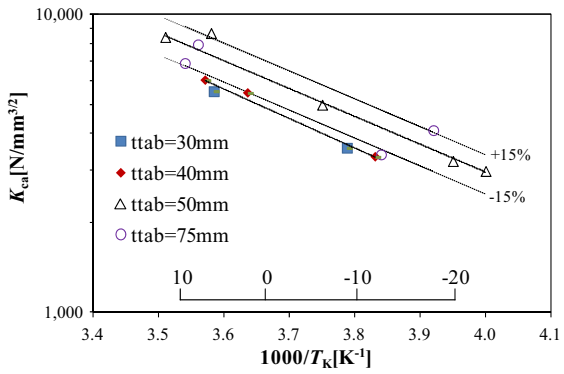


Fig. 8 Effect of the thin tab plate on the results of arrest toughness tests

Table 15 Chemical compositions [mass%]

Mark	Thickness (mm)	C	Si	Mn	P	S
Y36N30	30	0.14	0.41	1.45	0.017	0.003
Y32N80	80	0.14	0.40	1.42	0.016	0.003
Y36N50	50	0.13	0.40	1.43	0.014	0.003
Y36T30	30	0.11	0.21	1.31	0.014	0.002

Table 16 Mechanical properties

Mark	Thickness (mm)	YP (N/mm^2)	TS (N/mm^2)	vTrs(°C)
Y36N30	30	416	541	−40
Y32N80	80	355	518	−65
Y36N50	50	364	514	−72
Y36T30	30	453	528	−80

Two normalized steels of 50 mm and 80 mm thickness are used. Chemical compositions and mechanical properties are shown in Tables 18 and 19.

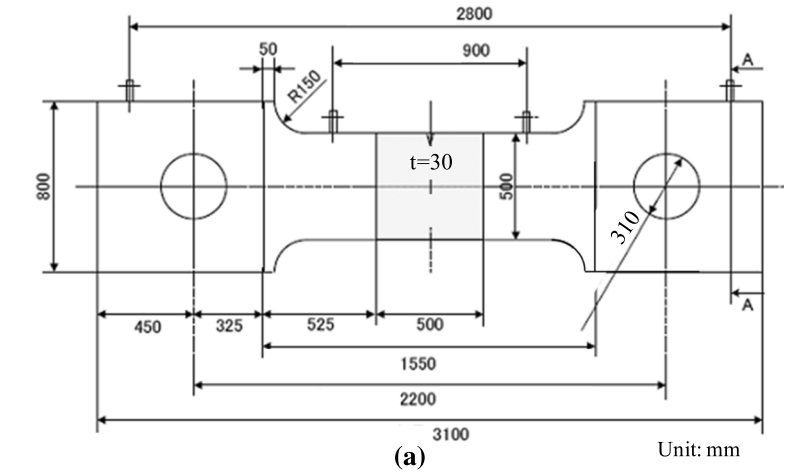
Temperature gradient type ESSO tests are conducted at three different steel mills in Japan. An example of the testing system is shown in Fig. 11a. Testing conditions are shown in Table 20. Duplex ESSO test is also conducted, which can be understand as no temperature gradient test. The testing system is shown in Fig. 11b. Suitable embrittled plates and welding consumables, which have proper toughness in the test temperature, are used in the duplex ESSO tests for straight and fast propagation of brittle crack through running plate and welded joint.

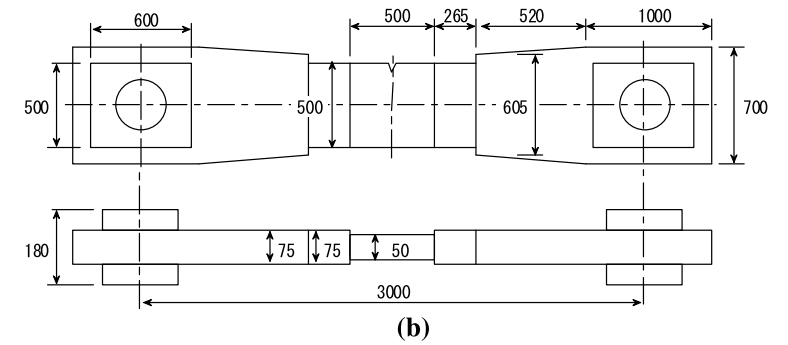
5.2 Results

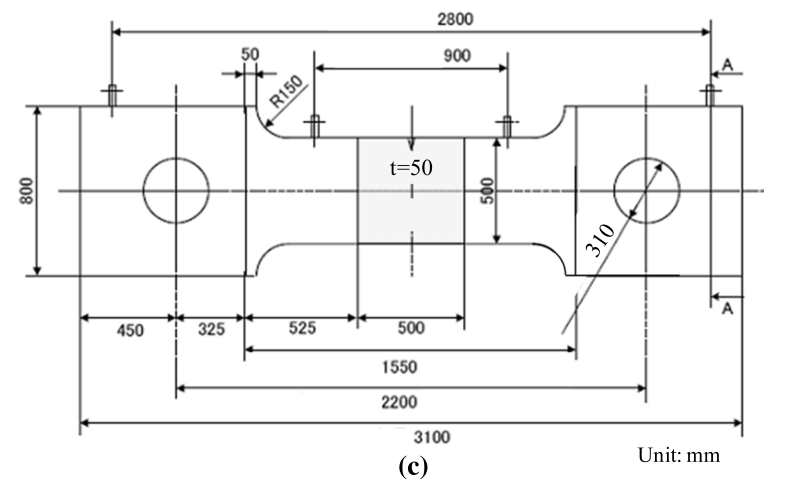
Test results are shown in Table 20, Figs. 12 and 13. K_{ca} values of larger temperature gradient condition show lower values than those of smaller temperature gradient condition in both N−1 and N−2. K_{ca} level estimated from results of duplex ESSO test is consistent with K_{ca} values of 0.25 °C/mm condition.

5.3 Discussion

Figures 12 and 13 indicate that K_{ca} value of 0.50 °C/mm condition may be too severe to evaluate the arrest in the actual structure which is usually under isothermal condition, i.e. without temperature gradient. From the above results, the temperature gradient as nearly equal 0.25 °C/mm is recommended.







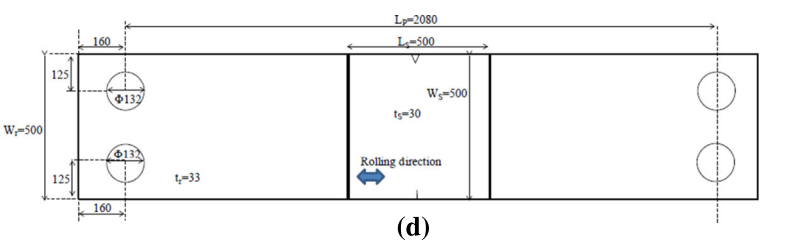


Fig. 9 Dimension of specimen on case of various high strength steel. **a** Specimen shape on Y36N30. **b** Specimen shape on Y36N50-1-4. **c** Specimen shape on Y36N50-5-10. **d** Specimen shape on Y36T30

Table 17 Testing conditions and results on case of various applied stress ration

Mark	Applied stress (N/mm^2)	Temperature at the crack arrest position (°C)	Arrest crack length (mm)	Arrest toughness value ($N/mm^{3/2}$)
Y36N301	102.3	−18.5	230	3037
Y36N302	204.6	−0.8	230	6075
Y36N303	61.4	−29.3	240	1881
Y36N304	131.1	−12.9	245	4083
Y32N801	87.9	−11.2	308	3348
Y32N802	175.5	6.3	251	5567
Y32N803	177.3	7.8	285	6265
Y32N804	176.9	12.1	400	7413
Y32N805	142.1	6.3	378	5663
Y32N806	141.7	6.5	526	6602
Y32N807	94.8	4.0	537	4495
Y36N501	147	−18.0	212	4131
Y36N502	98	−13.0	278	3393
Y36N503	196	10.0	287	6981
Y36N504	245	8.0	261	8021
Y36N505	98	−23.0	238	2984
Y36N506	147	−6.0	271	4967
Y36N507	294	6.0	228	8674
Y36N508	196	12.0	340	8359
Y36N509	132	−20.0	170	3210
Y36N5010	67	−32.9	215	1896
Y36T301	190	−12.7	241	5841
Y36T302	260	−9.2	249	8206
Y36T303	310	−11.7	226	9088
Y36T304	140	−18.8	254	4483

6 Conclusion

In this report, some of the effects of test conditions on the K_{ca} value evaluated by temperature gradient type ESSO tests are investigated. Investigation is based on the many temperature gradient ESSO type tests results with 16–80 mm thick low carbon steel produced by three research groups in Japan.

This investigation gives the appropriate range of test conditions as follows.

- The recommendation range of specimen width is 350–1000 mm. However, too narrow test specimens are likely to give too low values of K_{ca}, While, to use wide width specimen have little effect on K_{ca} values.
- The recommendation tab plate thickness is between from 0.8 times to 1.5 times the test specimen thickness. The recommendation tab plate width as 1.0–2.0 times the test specimen width affects little on the measured values of K_{ca}.
- The total length of the test specimen and the tab plates shall be larger than 3.0 times the test specimen width.
- The recommendation range of applied stress is less than 2/3 times yield stress at room temperature.
- The temperature gradient as nearly equal 0.25 °C/mm is recommended.

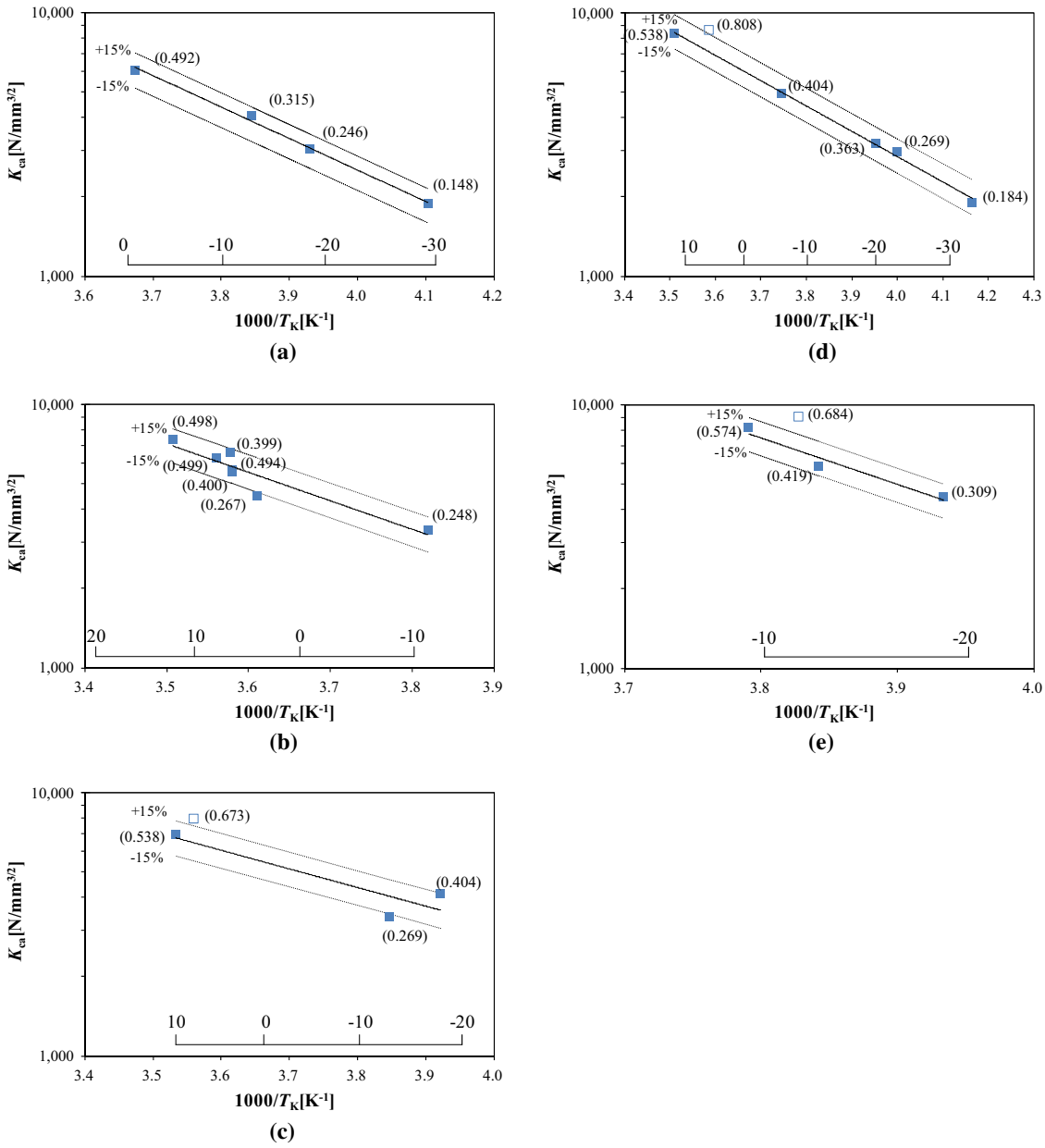


Fig. 10 Effect of applied stress on the results of arrest toughness tests. **a** Effect of applied stress on K_{ca} on Y36N30. **b** Effect of applied stress on K_{ca} on Y32N80. **c** Effect of applied stress on K_{ca} on Y36N50-1∼4. **d** Effect of applied stress on K_{ca} on Y36N50-5∼10. **e** Effect of applied stress on K_{ca} on Y36T30

Table 18 Chemical compositions [mass%]

Mark	Thickness (mm)	C	Si	Mn	P	S
N−1	50	0.13	0.40	1.43	0.014	0.003
N−2	80	0.16	0.42	1.51	0.011	0.004

Table 19 Mechanical properties

Mark	Thickness (mm)	YP (N/mm^2)	TS (N/mm^2)	vTrs(°C)
N−1	50	364	514	−72
N−2	80	366	532	−35

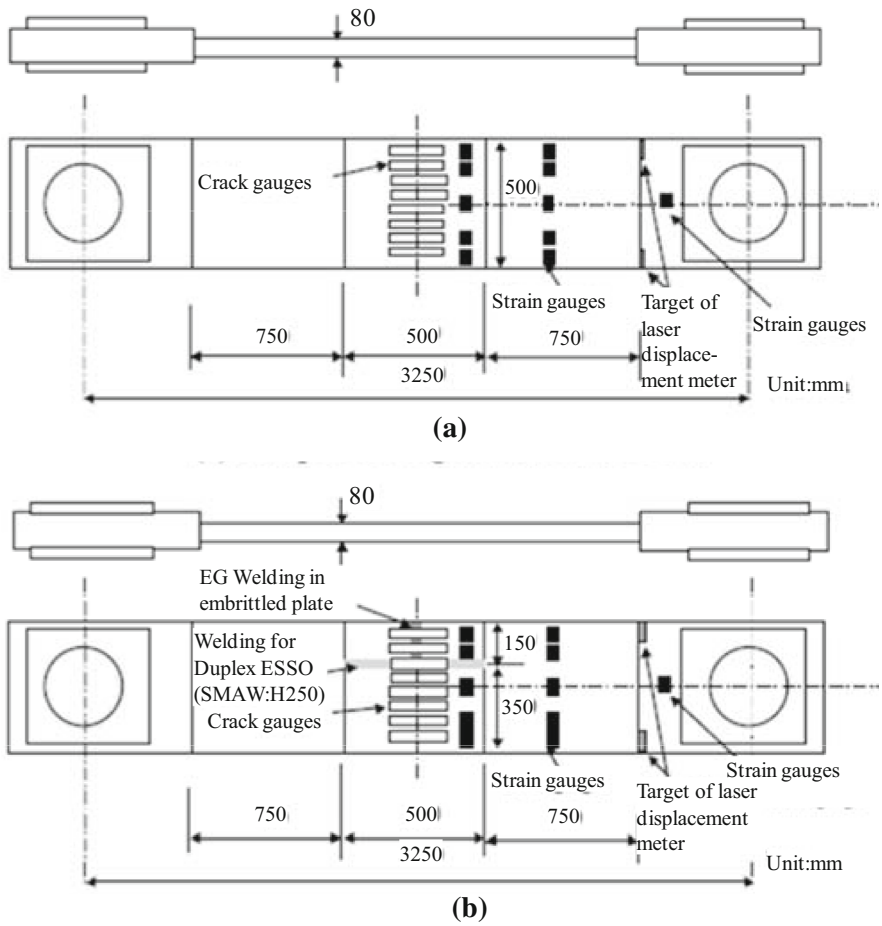


Fig. 11 Dimension of specimen and position of dynamic measurement. **a** Temperature gradient ESSO test **b** Duplex ESSO test

Table 20 Testing conditions and results on case of temperature gradient and duplex ESSO test

Mark TG : Temperature gradient DU : Duplex	Applied stress (N/mm^2)	Temperature gradient (°C/mm)	Temperature at the crack arrest position (°C)	Arrest crack length (mm)	Arrest toughness value ($N/mm^{3/2}$)
TG-N1-1	98	0.25	−23	238	2984
TG-N1-2	147	0.25	−6	271	4967
TG-N1-3	294	0.25	6	228	8674
TG-N1-4	196	0.25	12	340	8359
TG-N1-5	132	0.25	−20	170	3210
TG-N1-6	98	0.50	−10	273	3332
TG-N1-7	196	0.50	10	255	6296
DU-N1-1	147	0	−20	Go	–
DU-N1-2	123	0	−20	No-Go(203)	2776
TG-N2-1	156	0.28	19	306	5848
TG-N2-2	156	0.26	18	300	5788
TG-N2-3	120	0.25	15	313	4650
TG-N2-4	98	0.25	7	283	3440
TG-N2-5	83	0.25	10	311	3195
TG-N2-6	98	0.50	15	250	3099
TG-N2-7	156	0.50	25	248	4902
DU-N2-1	180	0	13	No-Go(217)	4063
DU-N2-2	216	0	13	No-Go(272)	4876
DU-N2-3	216	0	13	No-Go(163)	4876

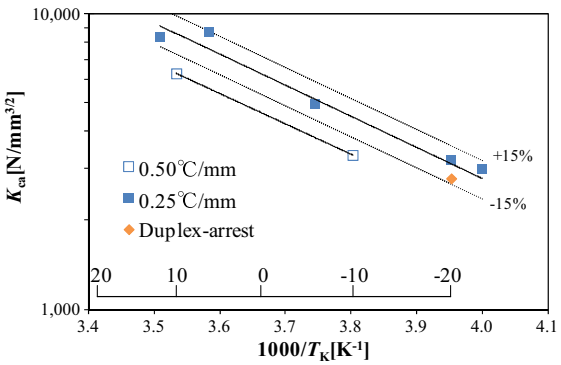


Fig. 12 Effect of temperature gradient and crack length on K_{ca} for N−1

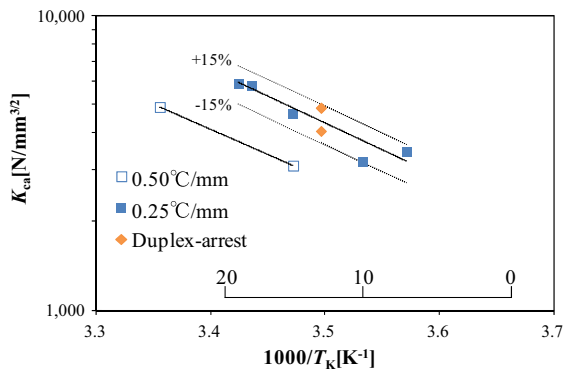


Fig. 13 Effect of temperature gradient and crack length on K_{ca} for N−2

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References

Aihara S, Shibanuma K, Watabe Y (2012) Development of numerical model for brittle crack propagation/arrest behaiviors (in Japanese). Jpn Soc Naval Archit Ocean Eng 16:109–120

Class NK (2009) Guidelines on brittle crack arrest design, pp 4–8

Kawabata T, Matsumoto K, Yajima H, Aihara S, Yoshinari H, Hirota K, Toyoda M, Kiyosue T, Inoue T, Hanada and T, Tani, (2010) Development of brittle crack arrest toughness K_{ca} test method—Brittle crack arrest design for ultra large container ships 2-. In: Proceedings of the 20th international offshore and polar engineering conference, Beijing 2010, pp 80–87

The Japan Welding Engineering Society (2014) Test method for brittle crack arrest toughness, K_{ca}