API Ballot 6582

Work Item Number	2413
Title of Work Item	**Effect of Side Groove on the Edge Cracks for Reducing Invalid Double Cantilever Beam tests**
Ballot Revision Level	1
Type of Ballot (Initial, Comment, Comment resolution (reference API ballot#), 1st Re-ballot, 2nd Re-ballot, etc.)	Comment
Submitter Name(s)	David Sponseller, Xin Long, Keiichi Kondo
API Document Modified	TR not published yet
Impacted Documents	None (standalone TR not referenced by another API document)
Revision Key	All black text due to initial ballot for first edition TR

Ballot Rationale: Edge cracks cause significant invalid DCB tests, which wastes lot of time for the testing. Previous studies show that some modification of the side groove can possibly reduce the edge cracks. This work item is to find out how effective this method can be by doing some DCB tests for various side groove configurations, grades and in various sour environments.

UPDATED SRRR CHARGE (Jan 2022) Draft and publish a technical report containing simulation, analytical, and experimental findings of effects of side groove geometry on Grade C110 DCB results, learnings, and conclusions. Communicate recommendations to AMPP for improving NACE TM0177.

Effect of Side Groove on the Edge Cracks for Reducing Invalid Double Cantilever Beam tests

API TECHNICAL REPORT 5DCB
FIRST EDITION, [MONTH] [YEAR]

Introduction

Background: For NACE TM0177-2016 Method D (Double Cantilever Beam test; DCB), it has been pointed out that edge cracks that prevent the progress of SSC (Sulfide Stress Cracking) to occur in API 5CT Grade C110, which affects the evaluation. It has been reported one of the causes is excessive stress concentration at bottom of the V shaped groove with root (R) 0.25mm specified in NACE TM0177, which helps to initiate an edge crack. ~~Optimization of side groove root configuration has been discussed in WI2413 (DCB side groove study).~~

Investigation on effect of side groove root: In terms of KI (stress concentration) distribution at the groove, effectiveness of U grooves on reducing the edge crack was shown. For Grade C110 in 1 bar H2S-saturated NACE Solution A, there is no significant difference in KIssc among the standard V and the U grooves. In addition, it was confirmed that there is no significant difference in compliance between each notch type.

Optimization of side-groove configuration: For Grade C110 in 1 bar H2S-saturated NACE Solution A, small differences in occurring edge crack among U grooves with R0.65 and R0.95. R0.65 mm is suitable to prevent both edge crack and non-planar.

Verification using DCB specimens machined by Third Party: For Grade C110 in 1 bar H2S-saturated NACE Solution A, the effectiveness of U shaped side groove was also verified using specimens machined by Third party.

Complementary verification: Also, in terms of inspection of edge crack, machining effect and verification for Grade C110 with heavier wall (coupling stock) in 1 bar H2S-saturated NACE Solution A, effectiveness of U groove was confirmed.

Conclusion: It is recommended to include the proposed U shaped groove with R0.65mm in NACE TM-0177 Method D as an option for Grade C110 to prevent the occurrence of edge crack for the following grade and test condition:

- API 5CT Grade C110
- 1 bar H2S-saturated NACE TM0177 Solution A, standard size DCB specimen

For other grades and/or test environments other than Grade C110 in Solution A, it may be applicable if the effectiveness of U groove can be validated and documented.

~~API WI2413 (DCB side groove study) agreed to include the proposed U side-grooves as an option in NACE TM-0177 Method D. API WI2413 (DCB side groove study) will propose it to the AMPP committee (SC08).~~

Effect of Side Groove on the Edge Cracks for Reducing Invalid Double Cantilever Beam tests

1 Scope

The fracture toughness calculated by NACE TM0177-2016 Method D (Double Cantilever Beam test; DCB) is evaluated by cracks that grow vertically with respect to the direction of opening stress due to wedge insertion. As shown in Figure 1, it has been pointed out that edge cracks that prevent the progress of SSC (Sulfide Stress cracking) occur in high strength low alloy oil country tubular goods such as API 5CT Grade C110 material (specified minimum yield strength is 760 MP), which affects the evaluation. When the test specimen specified in NACE TM0177-2016 standard is used, it has been reported one of the causes is excessive stress concentration at bottom of the V shaped side groove with root (R) 0.25mm, which helps to initiate an edge crack. If edge cracks occur, there is a risk that the results will be judged as an invalid by NACE TM0177-2016 standard, which wastes lot of time for testing due to the retest.

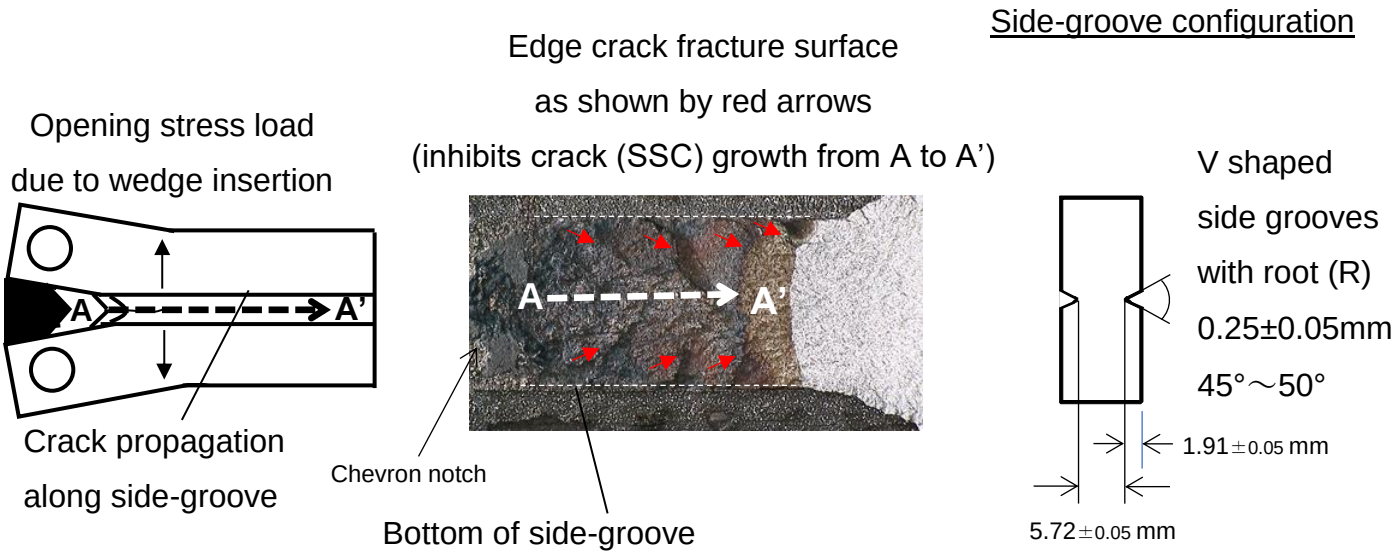


Figure 1—Effect of excessive stress concentration at the bottom of side groove

2 Investigation on effect of side groove root

The influence of various side-groove root configurations on edge fracture of DCB specimens was discussed because different types of side-groove roots are considered to change the stress concentration at the bottom of the side-groove and therefore affect the incidence of edge crack occurrence in the DCB test.

2.1 Testing Material

Verification was performed using API 5CT standard C110 grade actual steel pipe with heavy wall thickness, which was manufactured by Company A as a test material, was used for this investigation. The pipe size and mechanical properties were shown in Table 1. The chemical composition of the steel is shown in Table 2.

Table 1—Material

Material	Pipe size		Yield Strength		Tensile Strength	
	O.D.(mm)	W.T.(mm)	MPa	ksi	MPa	ksi
C110	305	36.6	786	114	874	126.8

Table 2—Chemical composition (mass %)

C	Mn	P	S	Cr	Mo
0.28	0.44	0.008	0.001	1.04	0.70

2.2 Methodology

2.2.1 Analysis of mechanical behavior of DCB test by FEA

Mechanical behavior of the DCB test specimen was calculated by FEA (Finite Element Analysis). The FEA conditions are shown in Table 3. The FEM analysis was conducted as elastic-plastic material with a stress-strain curve for C110 material.

As shown in Figure 2, 1/4 of the DCB test specimen was modeled in terms of the symmetry of the specimen. The boundary condition of symmetry was imposed on the XY and YZ planes of the specimen. The open displacement of the specimen was imposed along the Y direction.

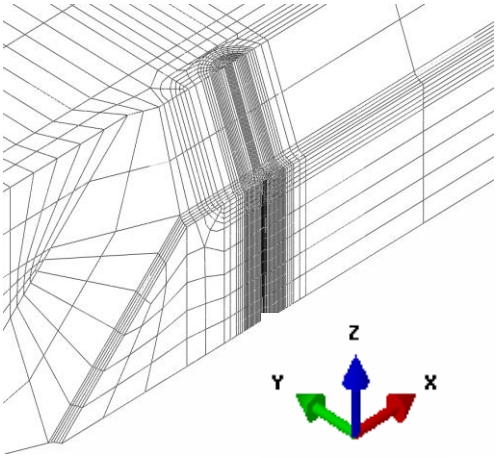
As shown in Figure 3, DCB specimen with different shapes of side groove were modeled. (a)V shaped groove with R0.25mm conforms to NACE TM0177-2016, (b) U shaped groove with R0.65mm, (c) U shaped groove with R0.80mm and (d) U shaped groove with R0.95mm have a large bottom root compared to (a). (b) was modeled as having the same area (volume) of the side groove as that of the specimen with that of (a). (c) was modeled as intermediate between (b) and (d). (d) was modeled as having the same side groove width as (a). Other sizes of DCB specimens were within the allowable dimensional range of NACE TM0177-2016. As K value at notch and crack tip is influenced by the mesh size and its shape, the same mesh size and shape were defined. The relationship between load and displacement at the various crack lengths can be obtained.

There were three types of crack starter configurations, which were chevron notch type, chevron notch with fatigue pre-crack (2mm) and EDM notch type shown in Figure 4. Crack start positions of three notched types of DCB specimens were in accordance with NACE TM0177-2016.

Table 3—FEA condition

FEA method	Plastic-Elastic Model Firstly, the -J integral value is analyzed, and then converted to K1 using the following conversion formula from J to K: K [MPa√mm]= √(e' *J) e' = E / (1 - Poisson's ratio^2)	
Notch type	Chevron notch, chevron notch with fatigue pre-crack, EDM notch	
Material property	Stress-Strain curve of C110 material	
Thickness	9.53mm	
Displacement	0.89mm: API 5CT alternative solution, 0.51mm: API 5CT standard	
Side groove	V shape with R0.25mm	U shape with R0.65mm, R0.80mm, R0.95mm

Note 1: 1/4 of the DCB test specimen was modeled.
Note 2: For entire DCB standard model,
please see
Figure 2 of NACE 2016 paper No. 7155
or
Figure 2 of NACE 2017 paper No.9102
Note 3: The boundary condition of symmetry was imposed on the XY and YZ planes.
Note 4: The open displacement of the specimen was imposed along the Y direction



Ex.) FEM model for near Chevron notch

Figure 2—FEM model for DCB specimen

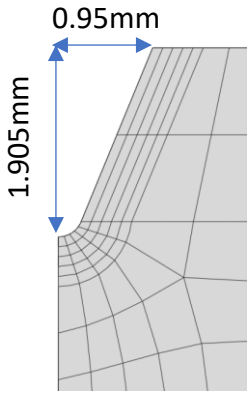
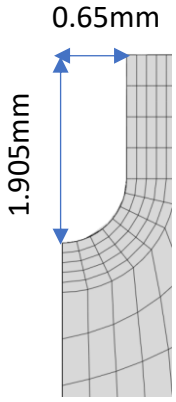
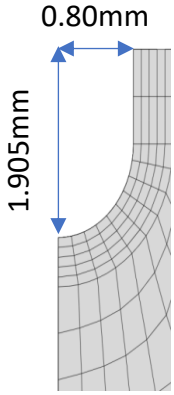
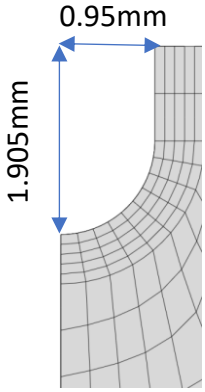
Side groove configuration	(a) V shape with R0.25mm	(b) U shape with R0.65mm	(c) U shape with R0.80mm	(d) U shape with R0.95mm
				
Remarks	Standard in NACE TM0177-2016	Area of side groove: equal to (a) standard V	Intermediate	width : equal to (a) standard V

Figure 3—DCB specimen configuration for FEA

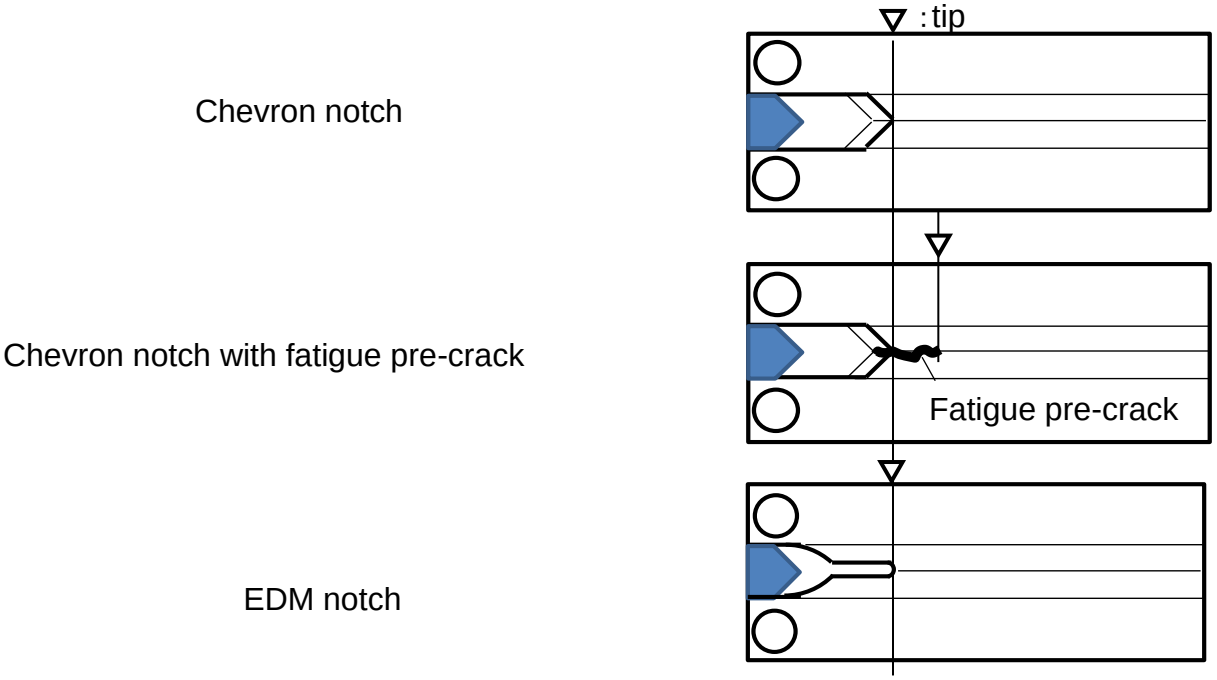


Figure 4—Each crack starter configuration in NACE TM0177-2016

2.2.2 DCB testing conditions

DCB tests were conducted to compare the occurrence of edge cracks on the DCB specimen with standard size and each side groove configuration as shown in Figure 3. Table 4 shows the test conditions. The test condition (A) is for the standard condition for API 5CT C110 material. The arm displacement was 0.51mm (+0.03/-0.05) as specified in API 5CT standard. The test condition (B) is a milder sour condition specified as NACE Solution D condition for API 5CT C110 material. The arm displacement was 0.89mm (+0.03/-0.05) in accordance with API 5CT standard. The test temperature was maintained at 24 ^{o}C (+/-1.0) by using isothermal bath with circulating water. Arm displacement was imposed by inserting a wedge with appropriate thickness into the slot of DCB specimen by vice method prior to immersion of the specimens. The test period was 14 days for the test condition (A) and 30 days for the test condition (B). The test duration of 30 days was set to avoid dry crack for this investigation. After immersion, the wedge was released at a speed of 0.5 mm/min using tensile testing machine. The wedge release stress can be obtained as a point (extreme pole) where the stress-displacement curve changes abruptly. Then, the specimen was cooled with liquid nitrogen, the fracture surface was broken with a hammer, the crack (Sulfide Stress Crack) growth surface was exposed, and the crack length was measured. K_{Issc} value was calculated by Equation (1) using the wedge release stress and crack length.

$$K_{Issc} \text{ (flat DCB test specimen)} = Pa\,(2\sqrt{3} + 2.38\,h/a)\,(B/Bn)^{1/\sqrt{3}}/Bh^{3/2} \qquad \text{Eq. (1)}$$

Table 4—DCB testing conditions

Classification	(A)	(B)
Specimen size	Standard size in NACE TM0177-2016	
Wedge material	Quenched material	
Wedge insertion	Vice method	
Test Vessel	Round shaped vessel（12 litter）+ isothermal bath	
Test Solution	5.0%NaCl+0.5%CH_3COOH	5.0%NaCl+0.4%CH_3COONa
Testing gas	Total pressure: 1 bar 100%H_2S gas	Total pressure: 1 bar 7%H_2S balanced with N_2 gas
Specified volume	1 litter / specimen	
Initial pH	2.6 to 2.8	3.8 to 4.0
Flow rate of testing gas	5ml/min / 1 litter of test solution	
Duration	336 hours	720 hours
Target arm displacement	0.51mm（+/-0.03）	0.89mm（+/-0.03）
Stirring of test solution	100rpm with magnet stirrer	
Temperature	24（±1.0）^{o}C	

2.3 Results

2.3.1 Effect of side-groove root configuration on compliance curve by FEA

Figures 5 to 8 shows the quality assurance plot calculated by FEA for the standard V shape and the U shaped grooves for which arm displacement (δ) is 0.89mm at the chevron notch, the chevron notch with fatigue pre-crack and the EDM notch types. The loads at the upper hole at the various crack tips are obtained by FEA and plotted on the quality assurance curve applied by Equation (2) specified in NACE TM0177-2016 appendix D. Each notch configuration with V shaped

groove in accordance with NACE TM0177-2016 was plotted between the ranges from maximum δ to minimum δ. In addition, each notch configuration with each U shaped groove was also plotted between the ranges from maximum δ to minimum δ. These results indicate that the compliance formula in NACE TM0177 2016 can be applied for the DCB specimen with each U shaped groove. In addition, as shown in Figure A, there is no significant difference in compliance among each notch type.

$$P/B=\delta E/(-26.232+51.866a/h+8.523(a/h)^2+8.5178(a/h)^3) \quad \text{Eq. (2)}$$

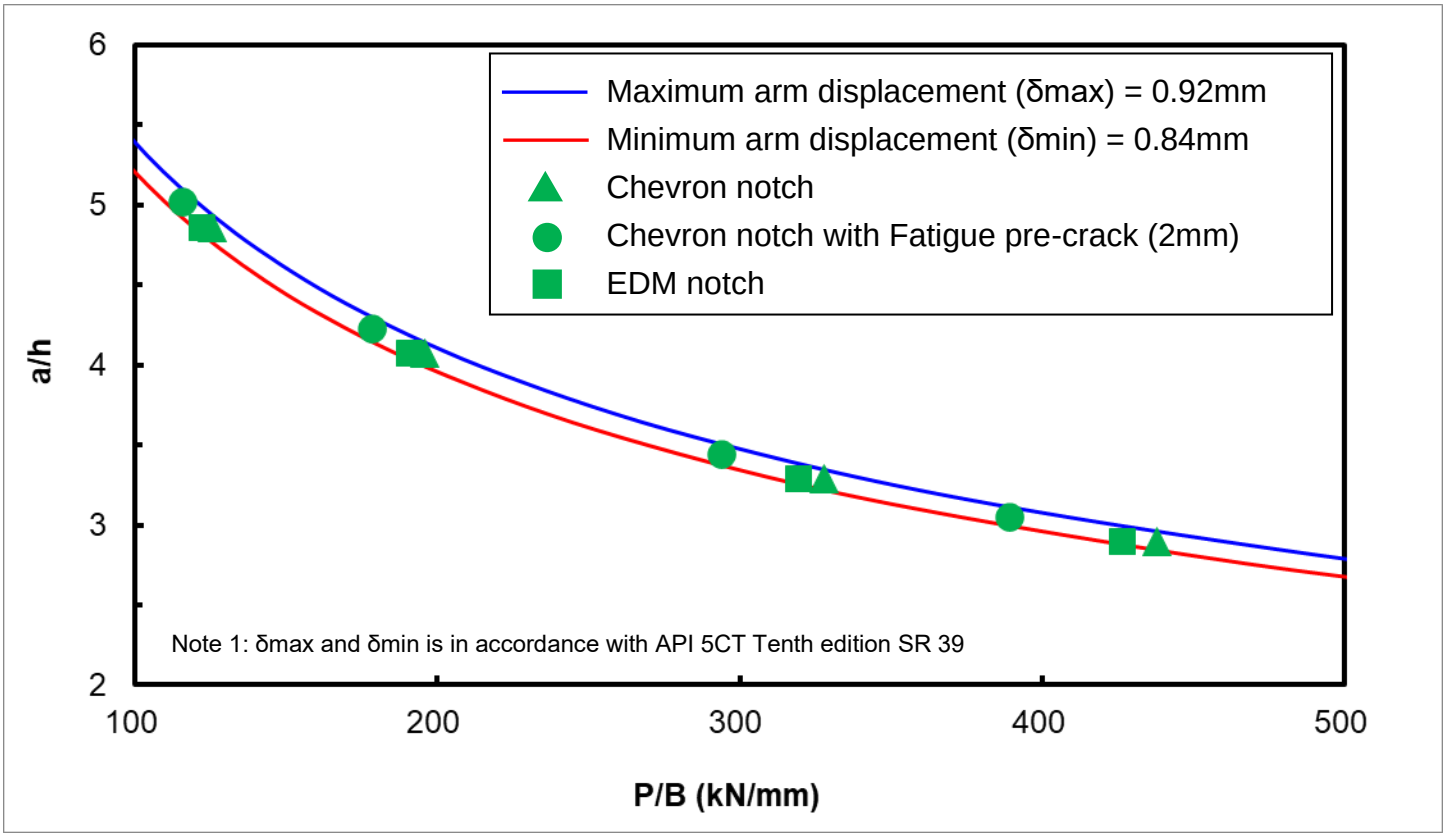


Figure 5—Compliance curve evaluation by FEA for the standard V shaped groove with R0.25mm

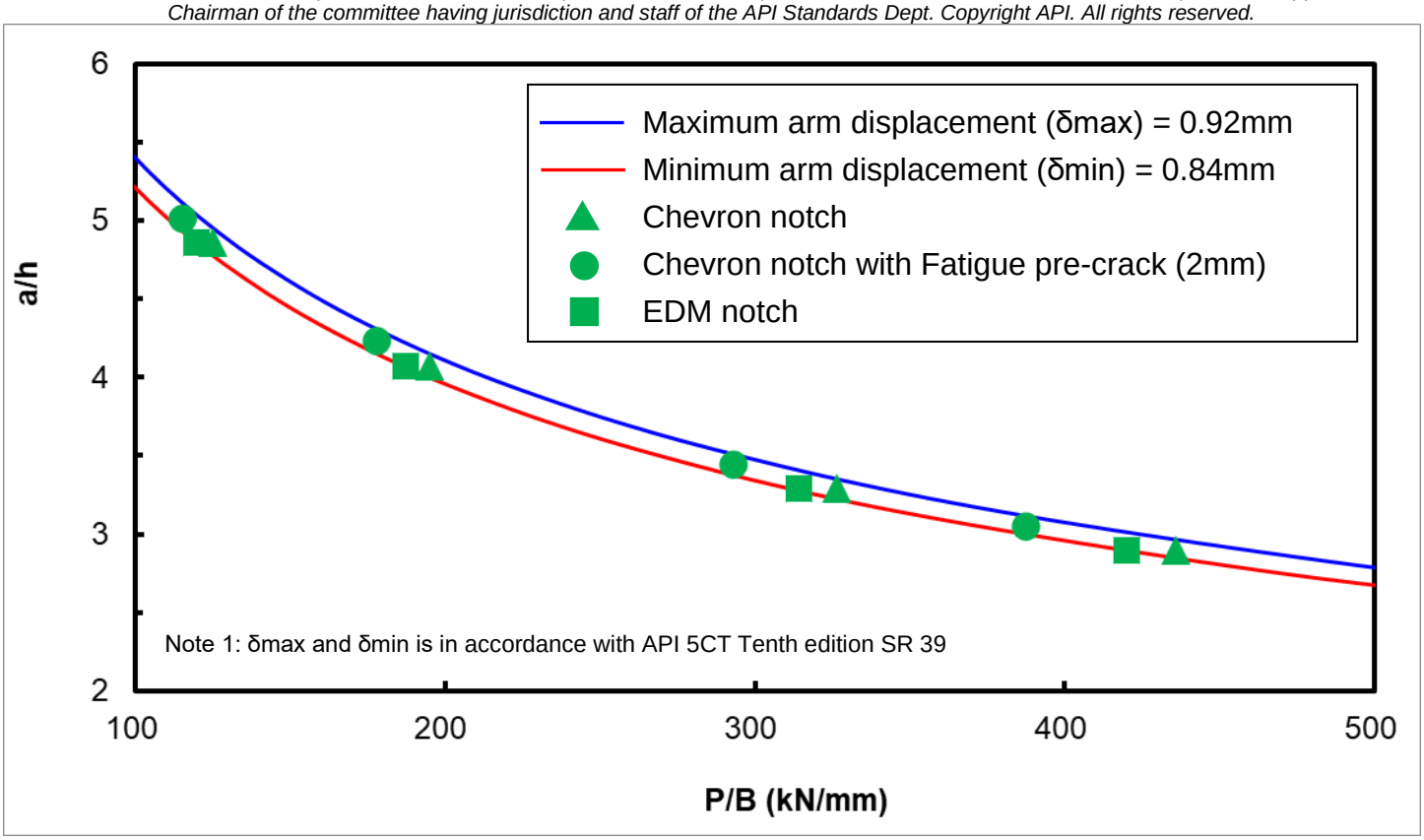


Figure 6—Compliance curve evaluation by FEA for the U shaped groove with R0.65mm

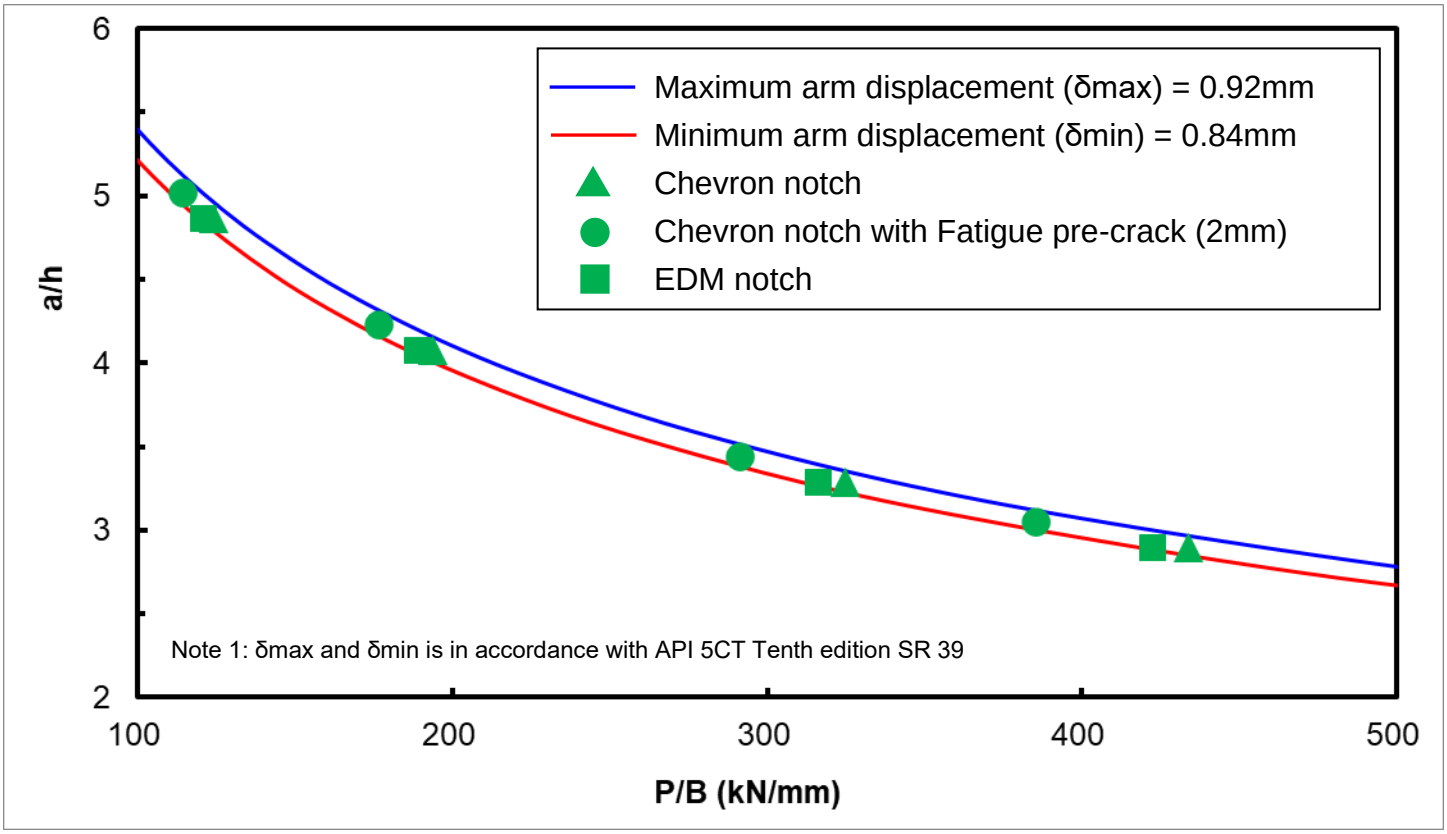


Figure 7—Compliance curve evaluation by FEA for the U shaped groove with R0.80mm

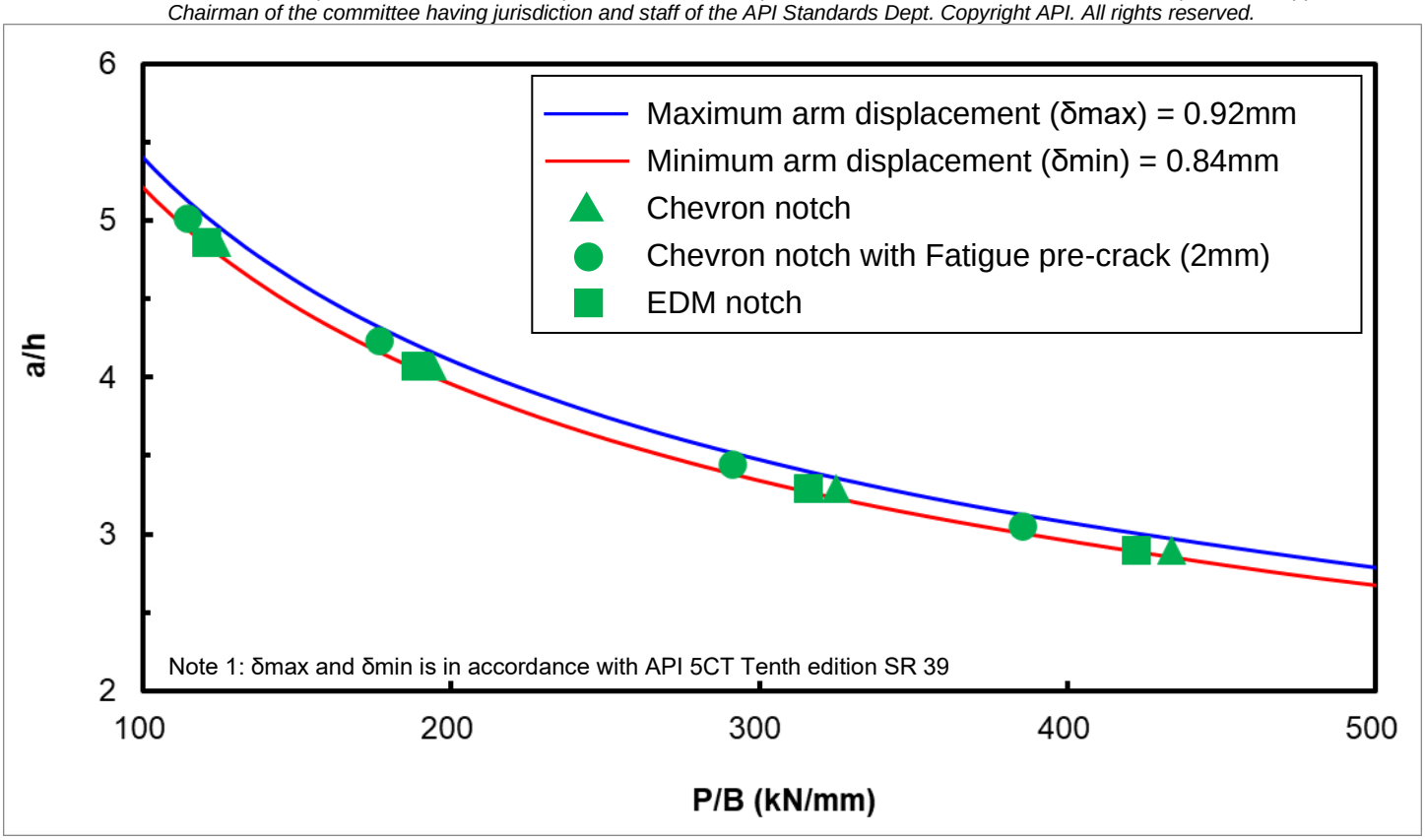
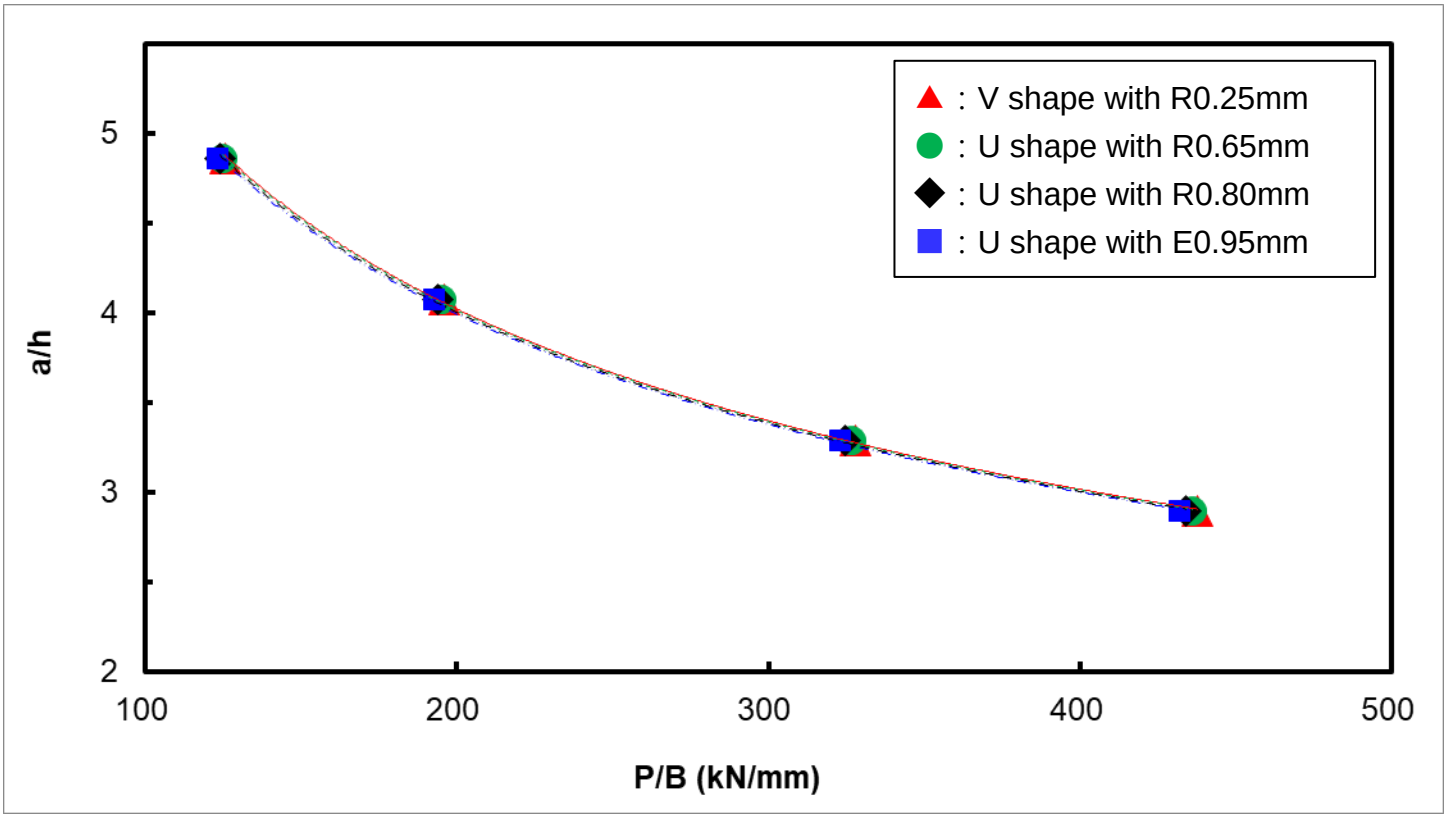
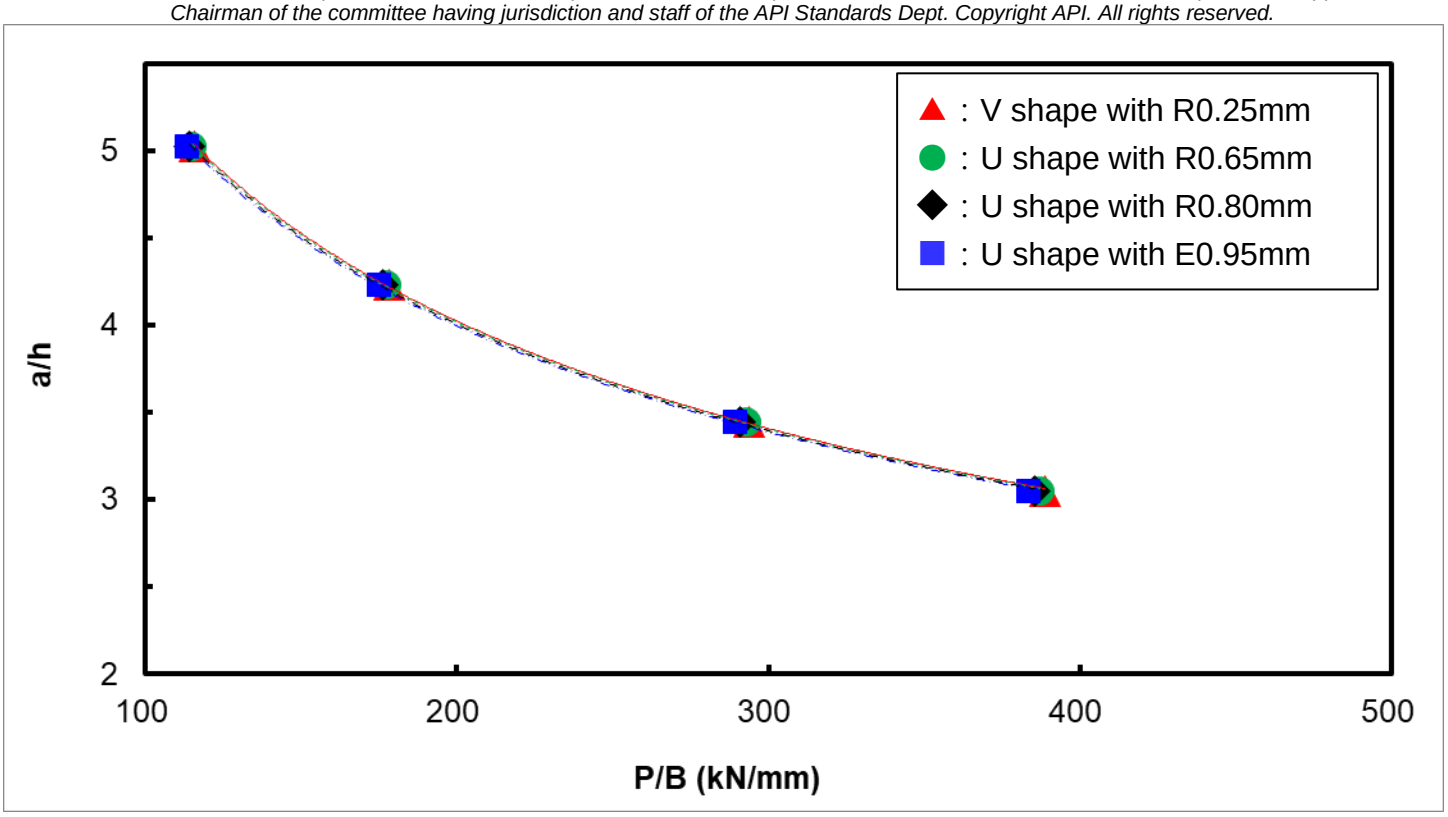


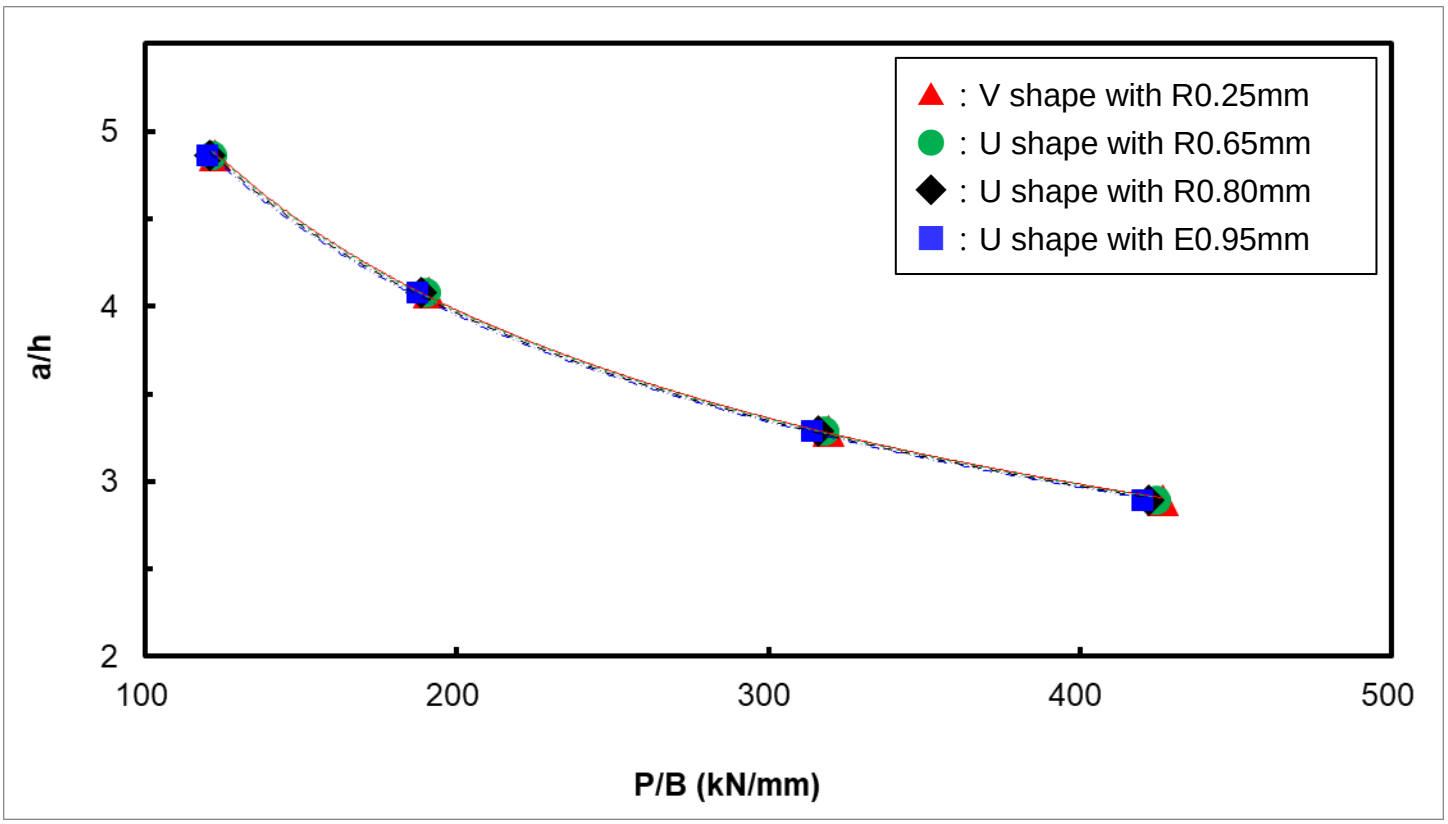
Figure 8—Compliance curve evaluation by FEA for the U shaped groove with R0.95mm



(a) Chevron notch



(b) Chevron notch with fatigue crack (2mm)

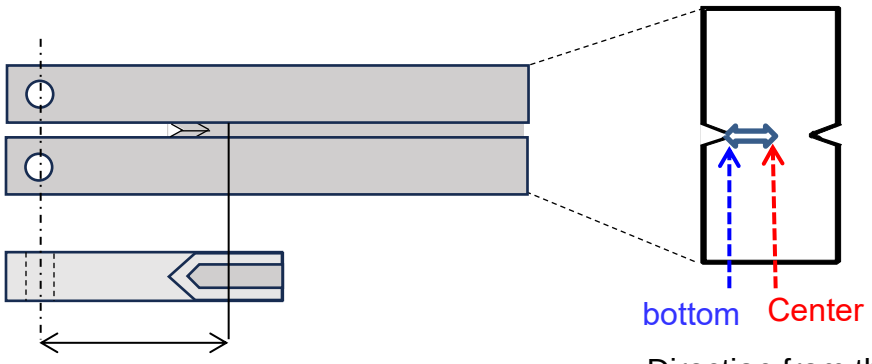


(c) Shift change of EDM notch

Figure A—Compliance curve evaluation by FEA

2.3.2 Effect of side-groove root on K value by FEA in case of (δ=0.89mm, ai=33.75mm)

Figure 9 shows the through-wall K value distribution, for which the arm displacement (δ) is 0.89 mm at the initial crack length (ai) of 33.75 mm from the hole, as calculated by FEA. The stress intensity factor K value at bottom of the side-groove decreased with an increase in the side-groove root (R). The K value at bottom of the side-groove was higher than that at center of thickness. Cracks can propagate at bottom of the side-groove more easily than at center of the width.



a: Crack length
(from the center of the hole to ~~to~~ the tip of the crack)

Direction from the groove bottom to the center is defined as X-axis

Definition of X axis

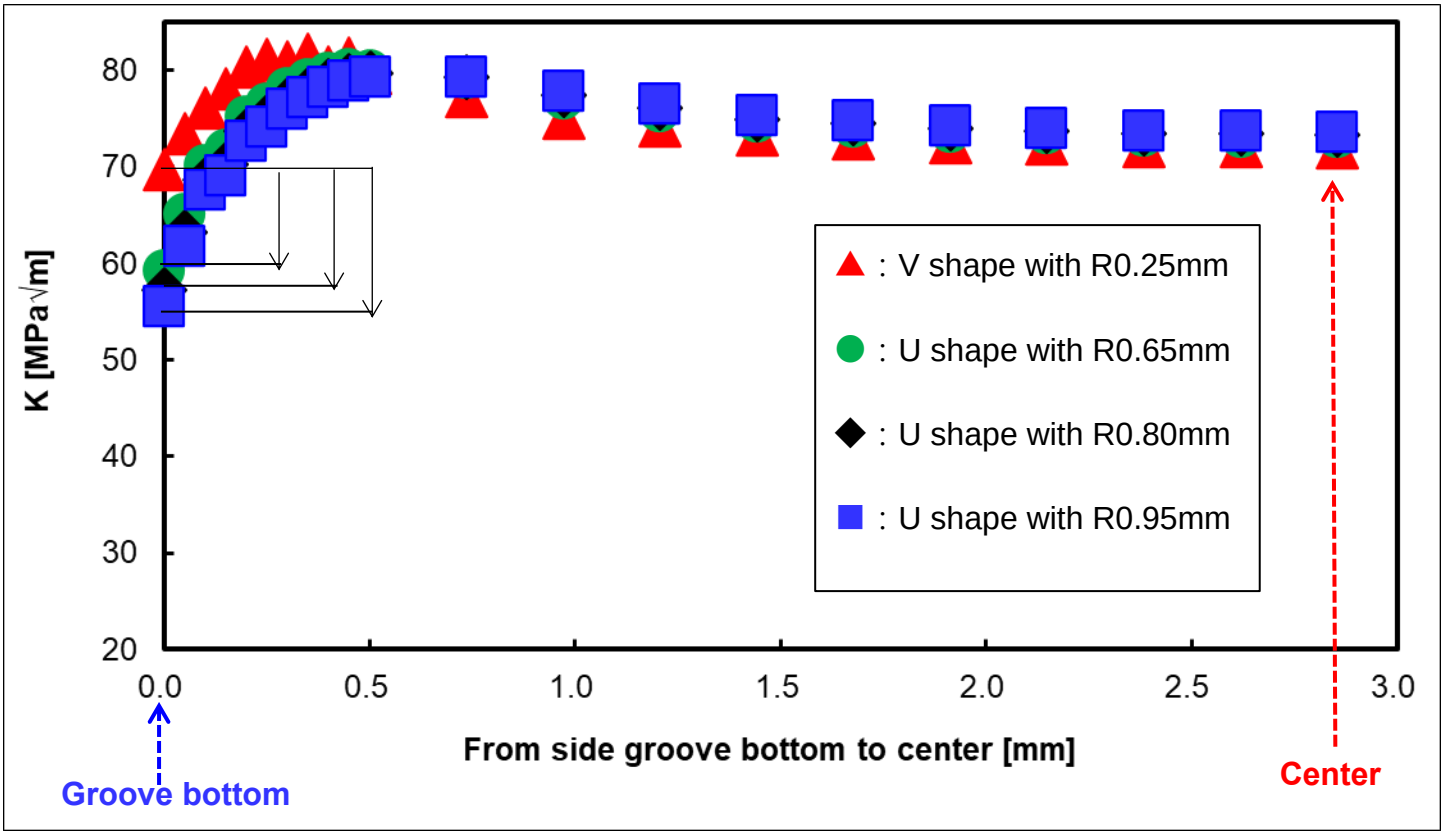
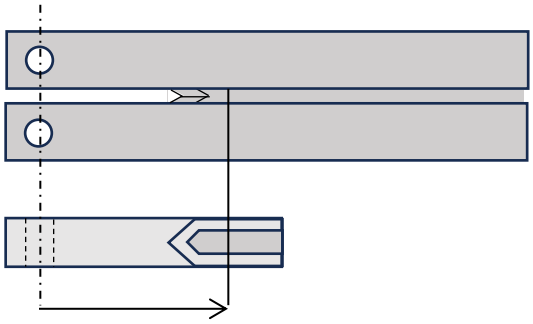


Figure 9—Through-wall K distribution

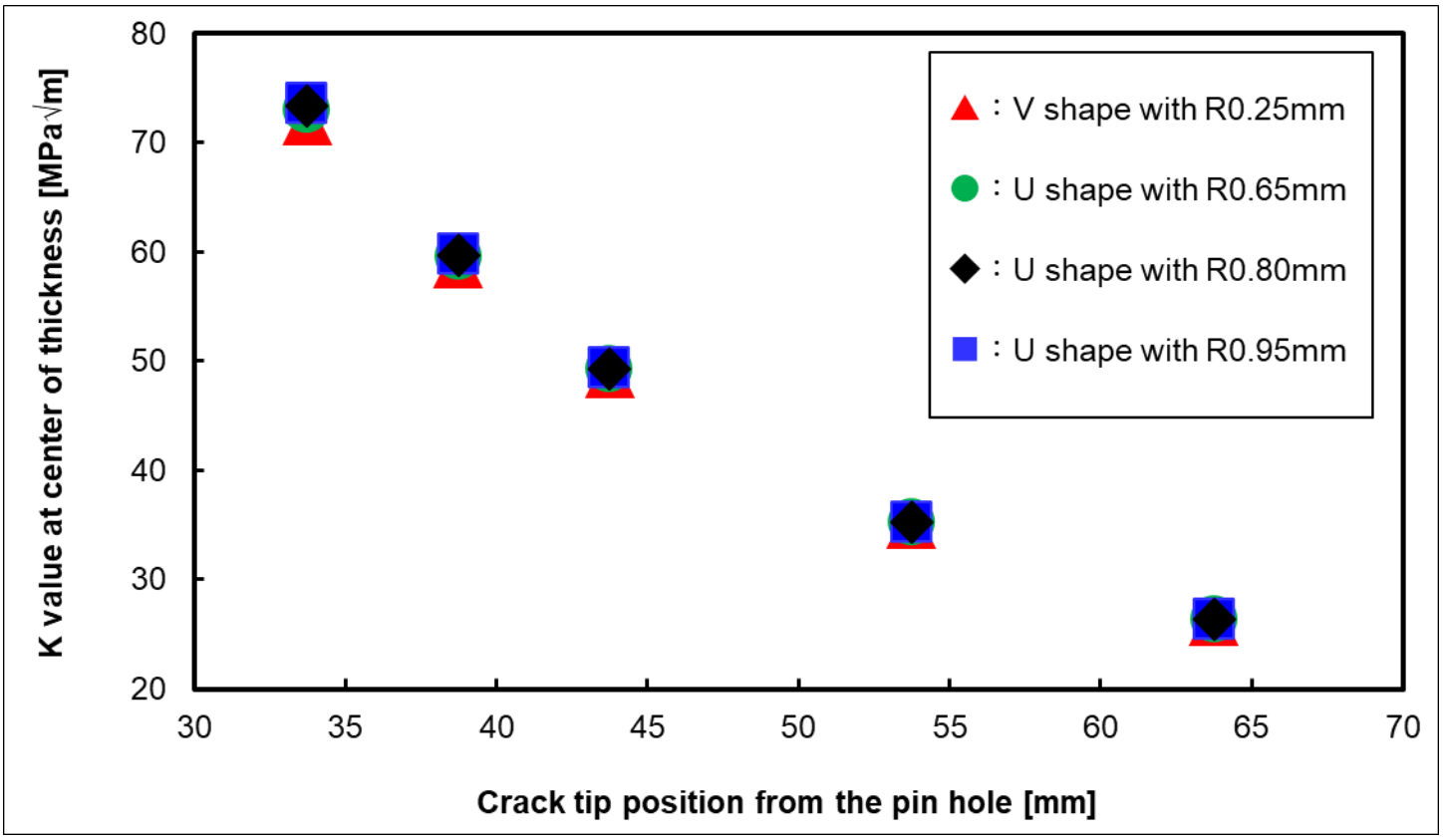
Figure 10 shows the K value at center of the width and bottom of the groove at the various crack length using the V shaped and each U shaped groove. Figure 10 (a) is the definition of X-axis. Figure 10 (b) is the K value at center of the

side groove and Figure 10 (c) is the K value at bottom of the width. The K value at the center of width of each U shaped groove is same as that of the standard V shaped groove. On the contrary, the K value at bottom of each U shaped groove is significantly small compared with that at bottom of the standard V shaped groove. These results indicate that the stress intensity factor at bottom of the side-groove has a strong effect on the edge crack initiation, and the same criteria as the standard V shaped side-groove configuration in NACE TM0177-2016 can be applied for the U shaped side-grooves.

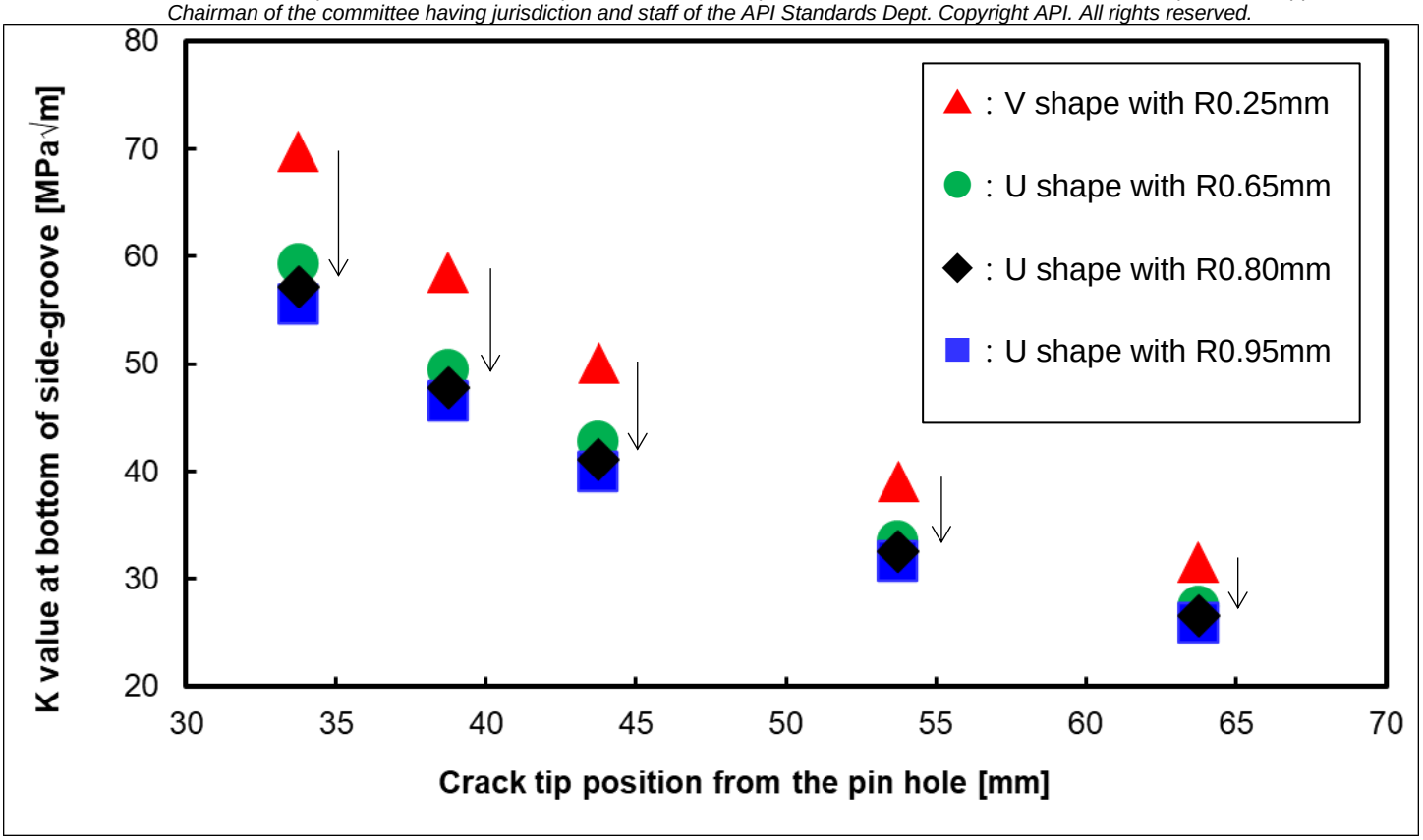


Direction from center of the hole to crack tip is defined as X axis

(a) Definition of X axis



(b) At center of width of side groove

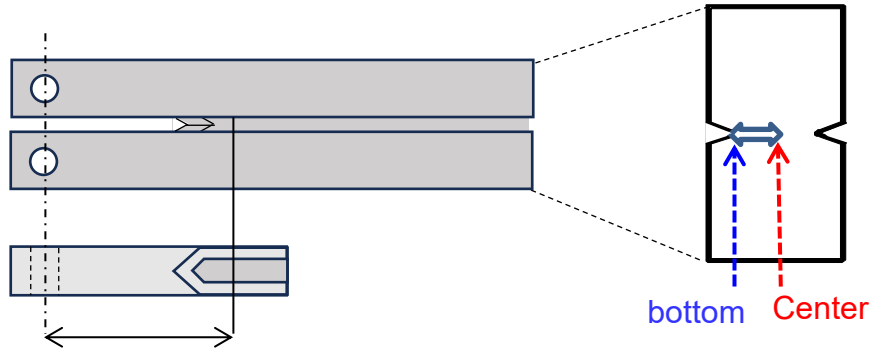


(c) At bottom of side-groove

Figure 10—Effect of side-groove configuration on K value

2.3.3 Effect of side-groove root on K value by FEA in case of (δ=0.51mm and 0.89mm, ai=31.75mm)

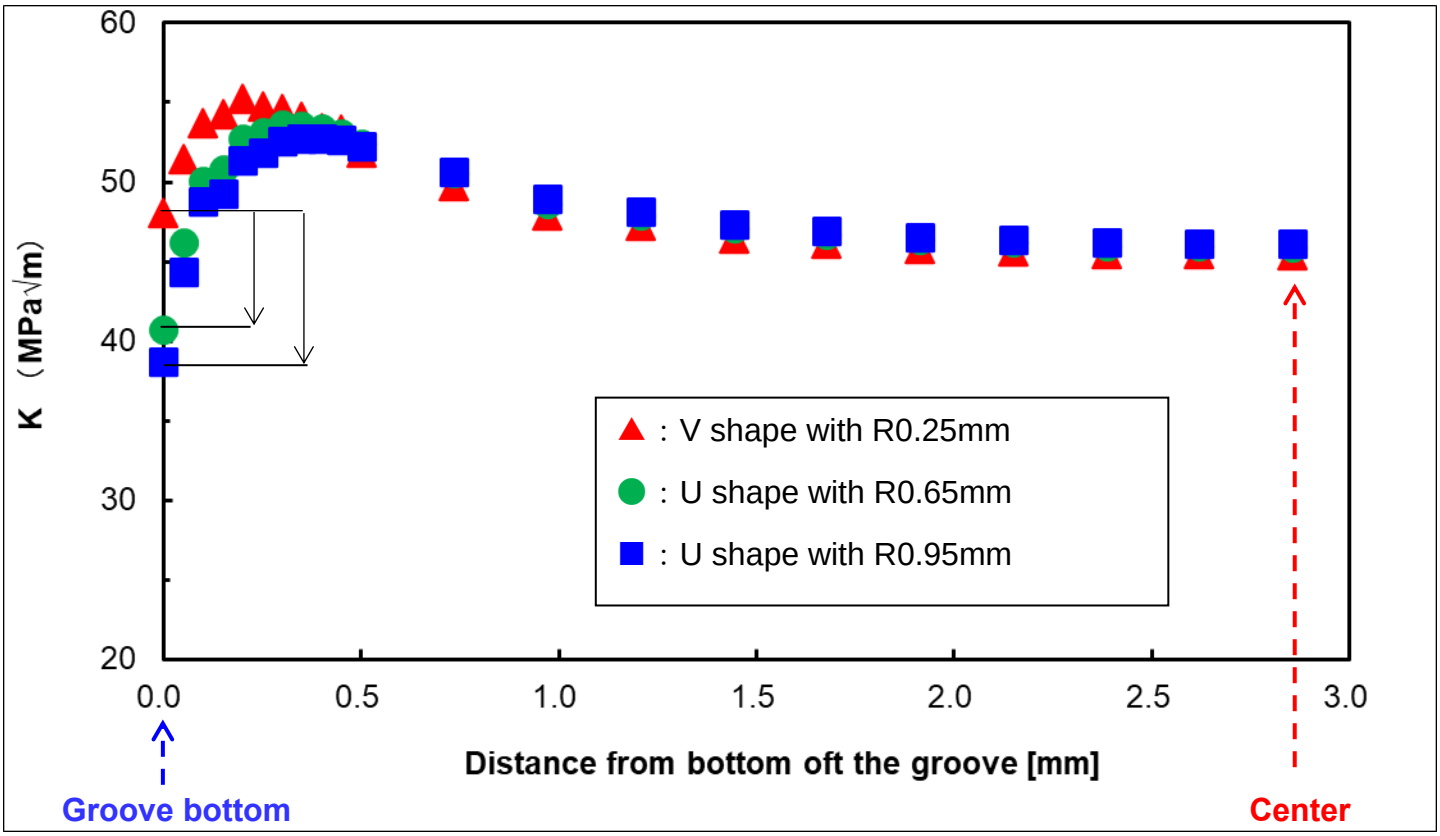
For DCB specimens with each shaped groove, FEA was performed to evaluate the distribution of K from bottom of the groove to center of the width when the initial crack length (ai) is 31.75mm. The results are shown in Figure 11. Figure 11 (a) shows definition of the X-axis. Figure 11 (b) shows the results for δ=0.51mm. Figure 11 (c) is for δ=0.89mm. As a common feature, after reached to maximum K towards from bottom of the side groove to the inside, it decreases toward center of the width. The major difference among each specimen was found in the K distribution within the range of the maximum K from bottom of the side groove. The larger root of the bottom, the smaller K near the bottom.



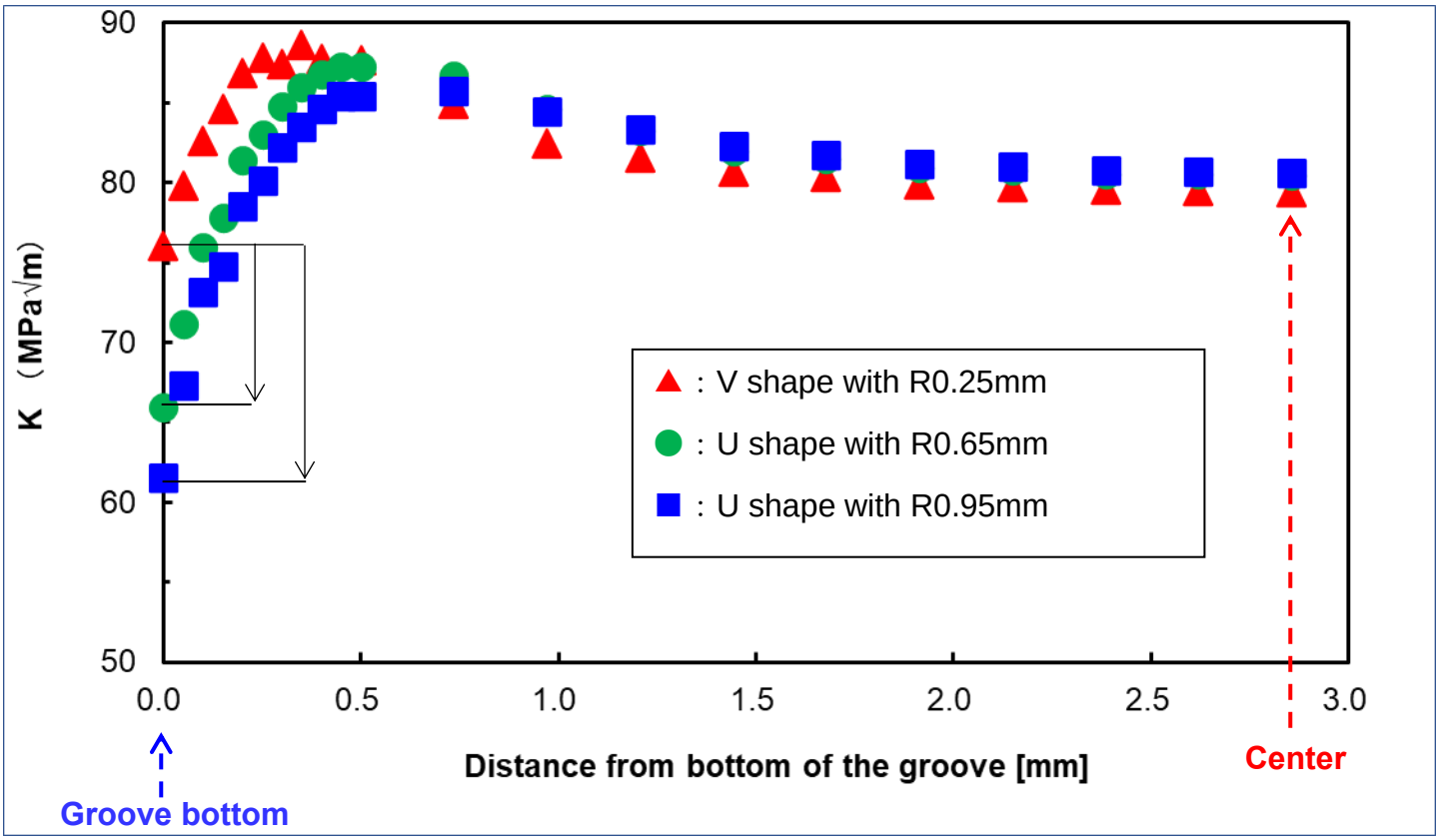
a: Crack length
(from the center of the hole to the tip of the crack)

Direction from the groove bottom to the center is defined as X-axis

(a) Definition of X axis



(b) Arm displacement (δ) = 0.51mm

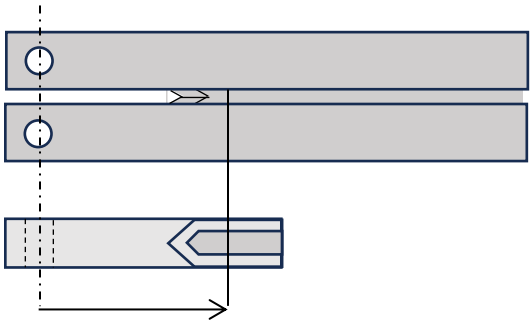


(c) Arm displacement (δ) = 0.89mm

Figure 11—Comparison of K distribution at crack length "a"= 31.75mm

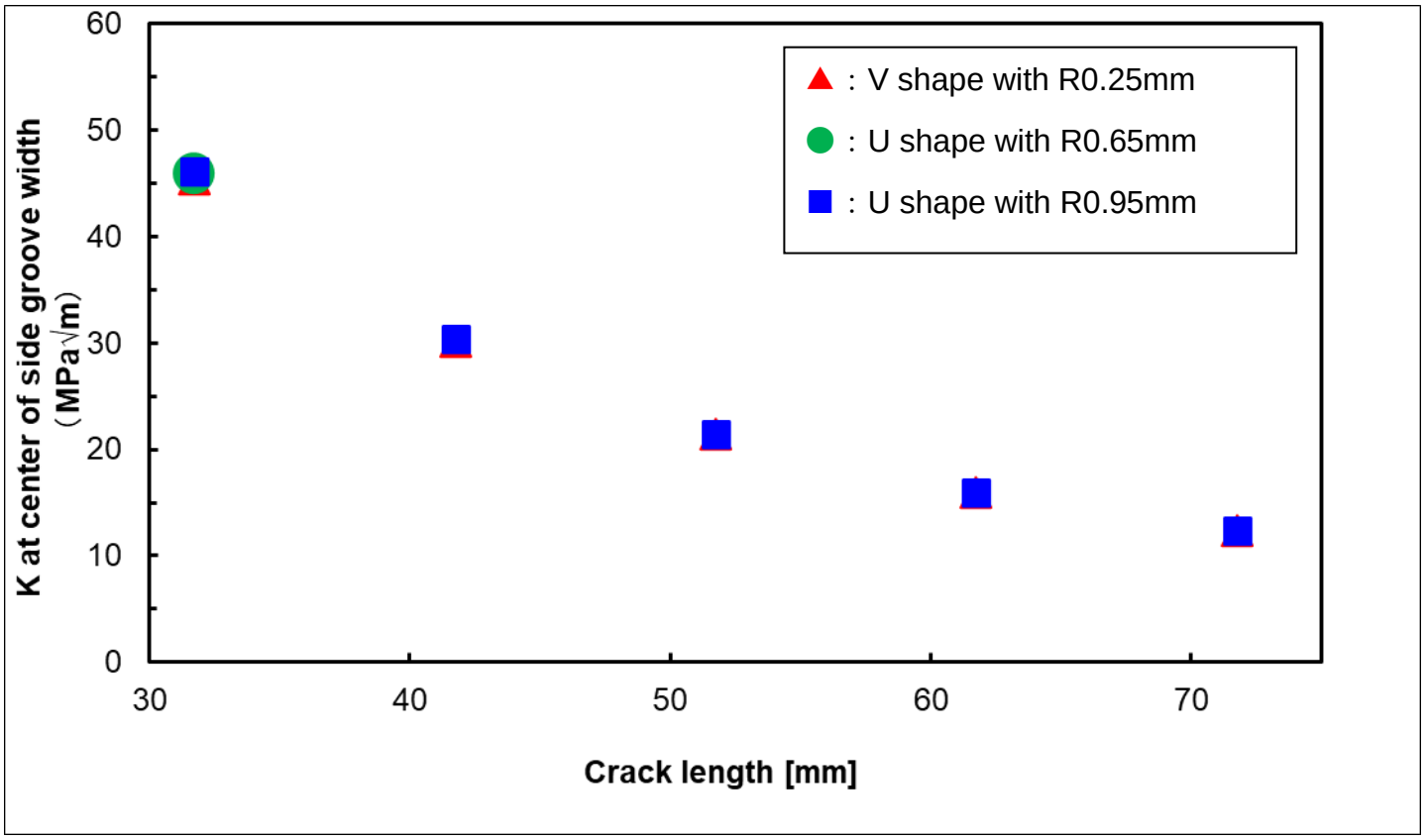
Figure 12 shows distribution of K at center of the groove width when varying distance from center of the hole to crack tip. Figure 12 (a) shows the definition of the X-axis. Figure 12 (b) is for δ=0.51mm and Figure 12 (c) is for δ=0.89mm. There is no significant difference in the variation of K at center of the side groove width among the standard V shaped groove with R 0.25mm and the U shaped grooves with R0.65mm and with 0.95mm.

While, Figure 13 shows the distribution of K at bottom of the groove in case of (a) δ=0.51mm and (b) δ=0.89mm. At the bottom of the side groove, the U shaped grooves with R0.65mm and 0.95mm shows lower K for the crack growth direction than the standard V shaped groove with R 0.25mm.

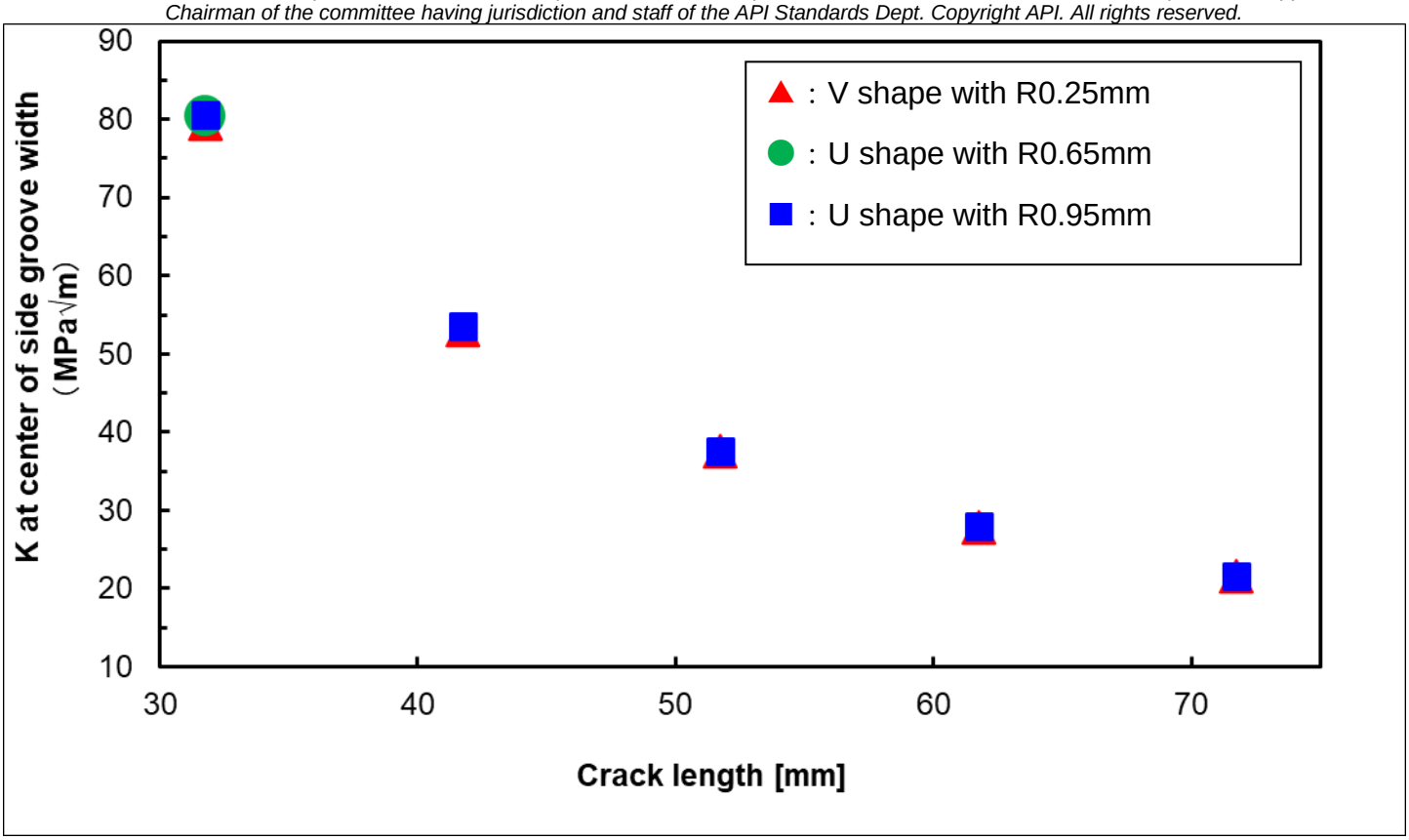


Direction from center of the hole to crack tip is defined as X axis

(a) Definition of X axis

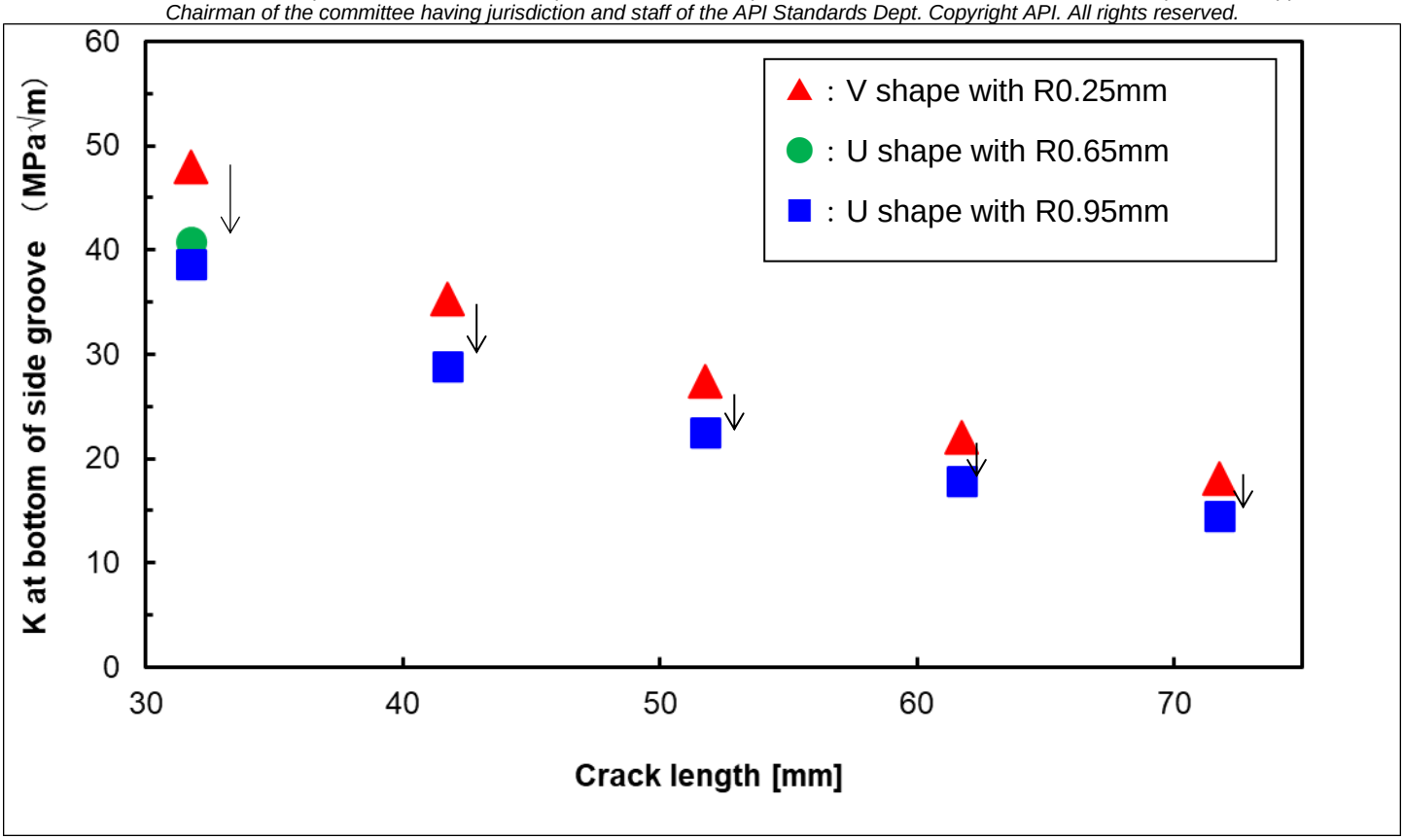


(b) Arm displacement (δ) = 0.51mm

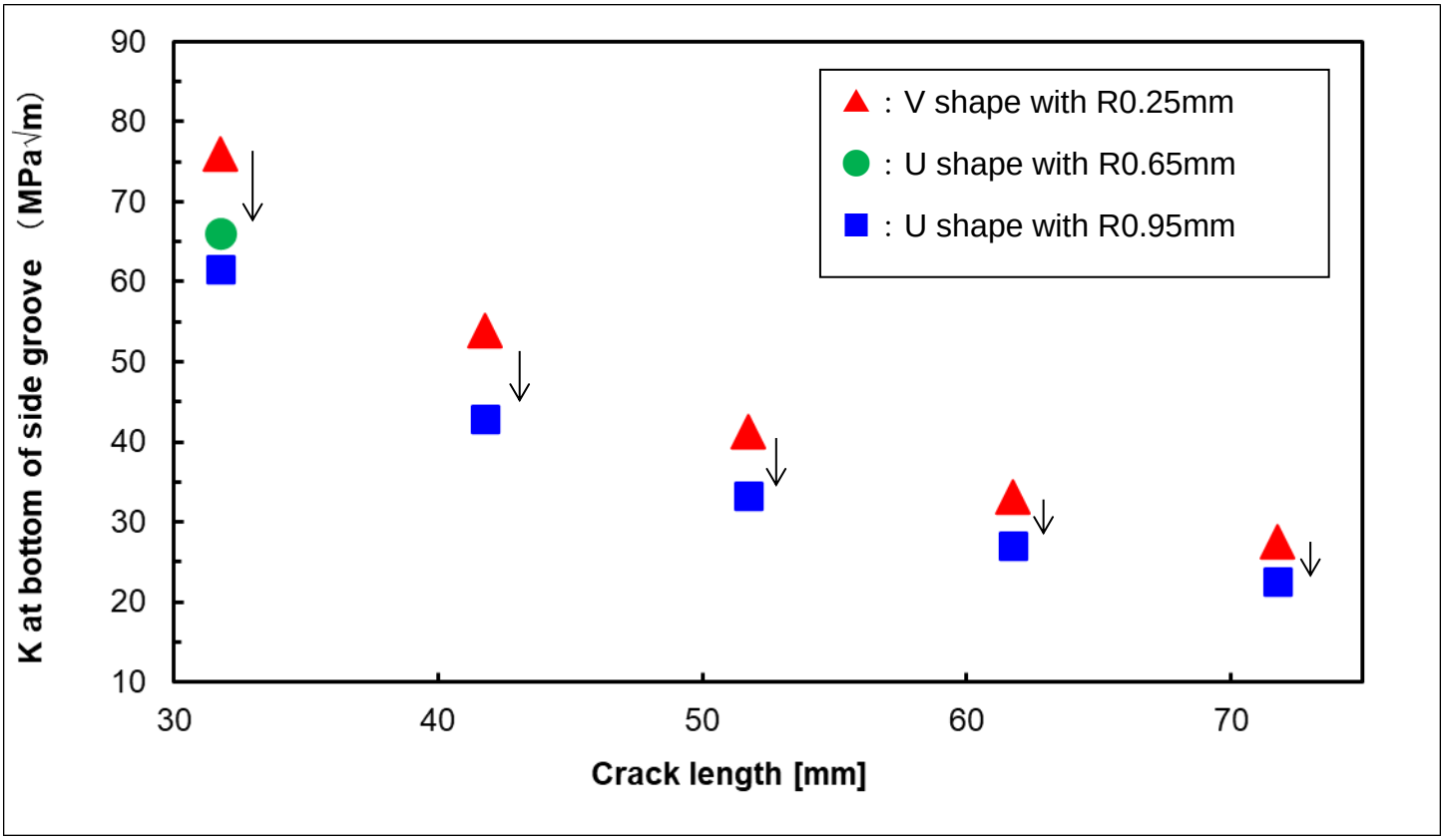


(c) Arm displacement (δ) = 0.89mm

Figure 12—Variation of K distribution at center of the groove width for direction of crack propagation



(a) Arm displacement (δ) = 0.51mm

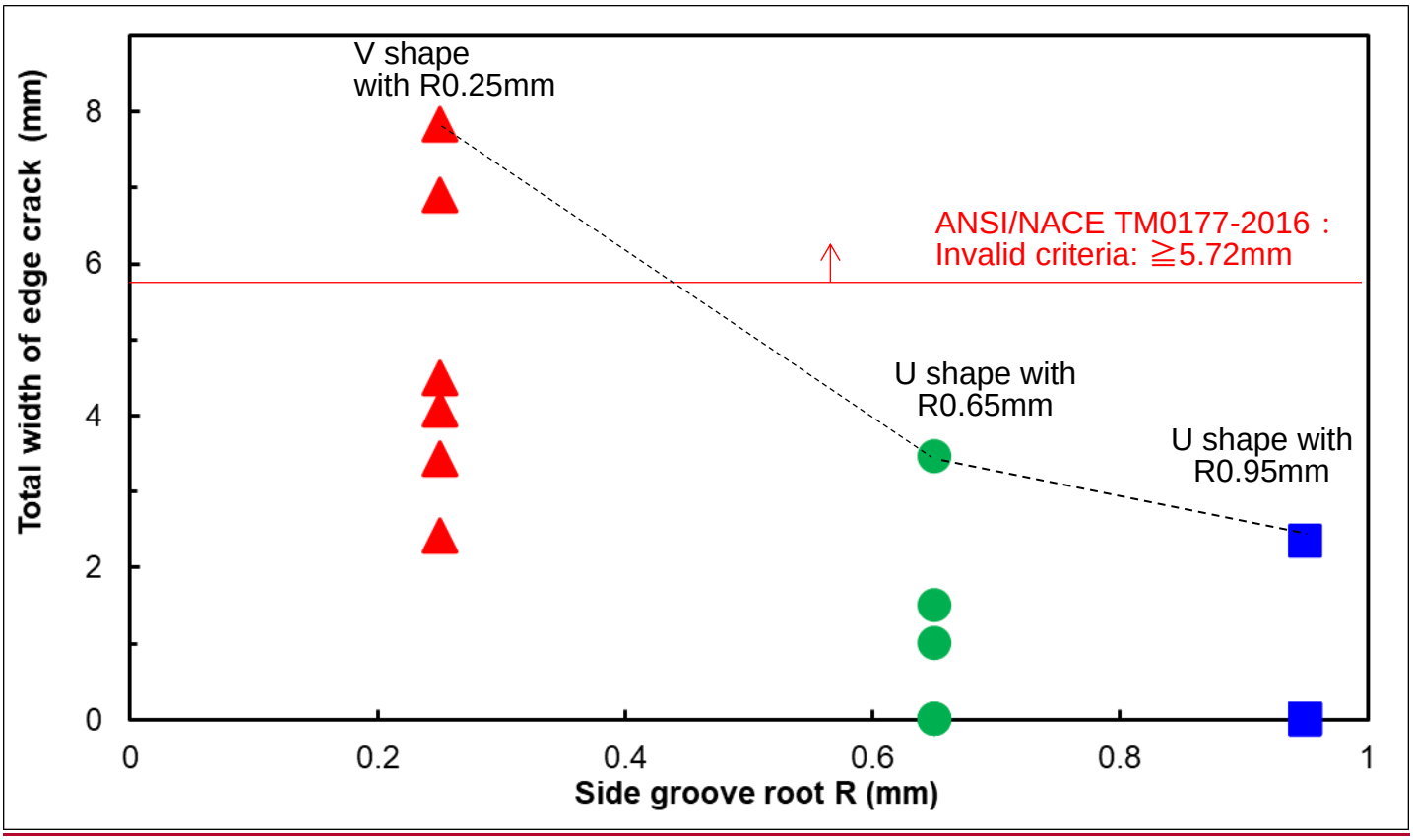


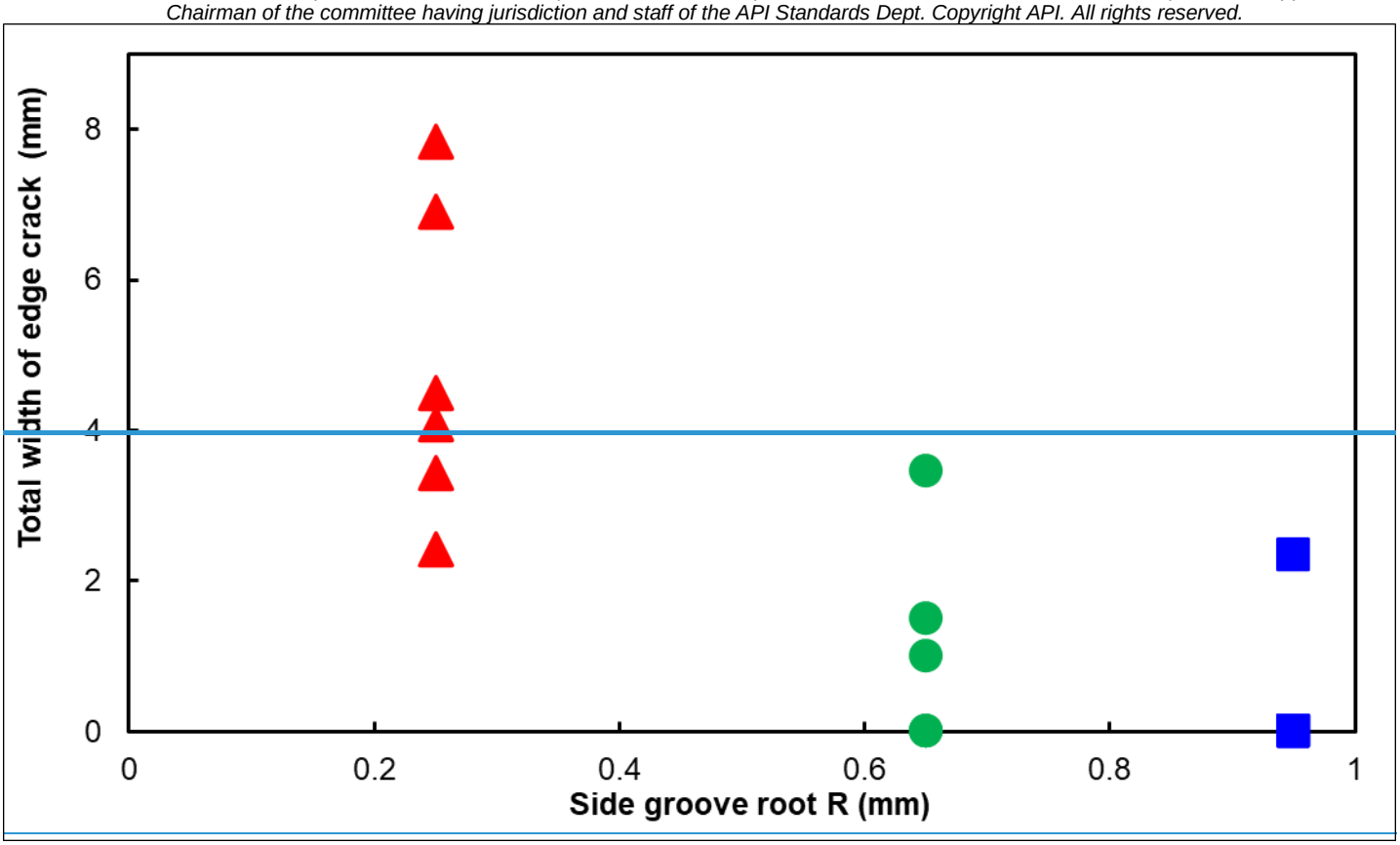
(b) Arm displacement (δ) = 0.89mm

Figure 13—Variation of K distribution at bottom of the groove for direction of crack propagation

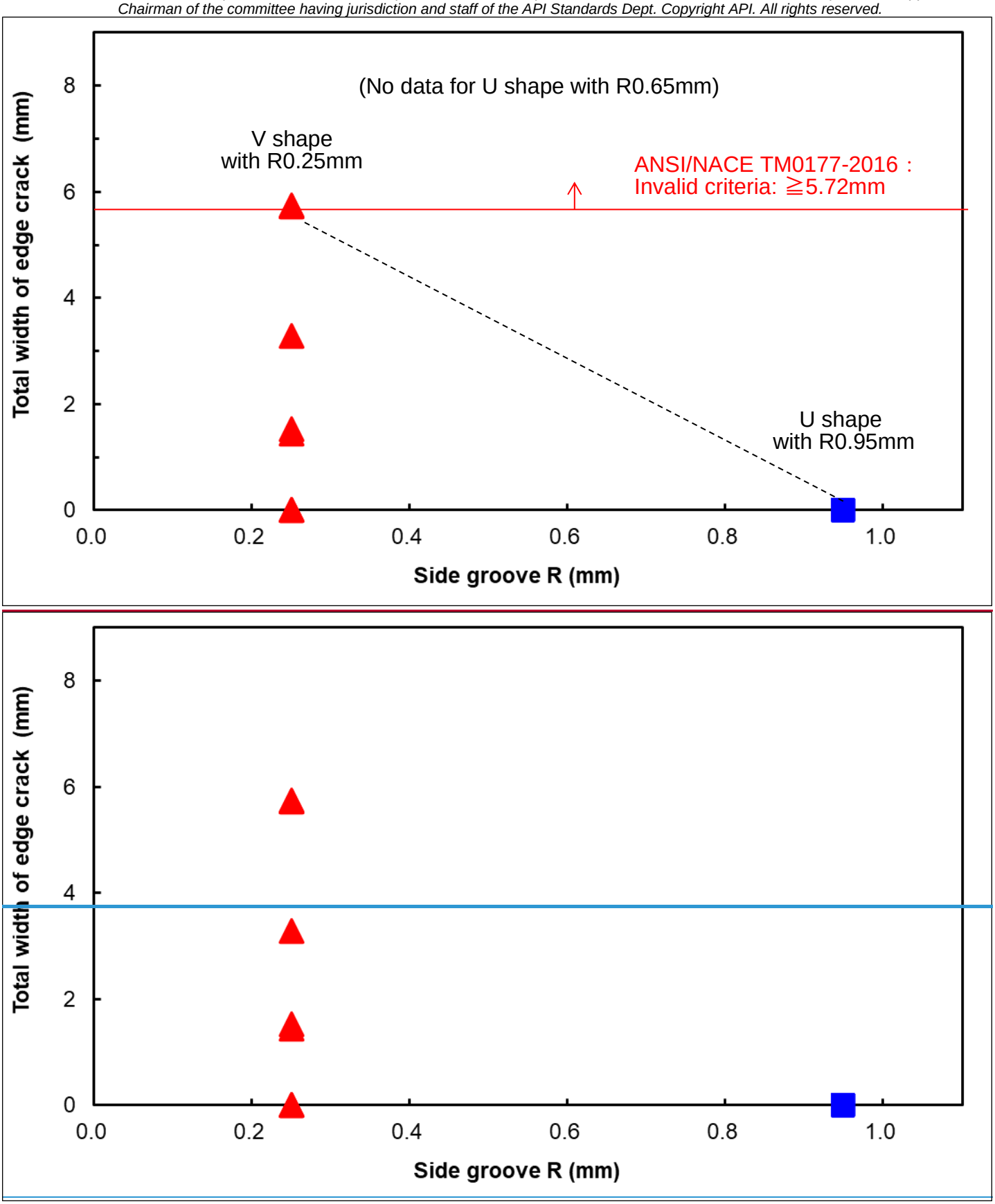
2.3.4 Results of DCB testing

Figure 14 shows the results of evaluating the relationship between the groove bottom root (R) and the edge crack length in the DCB test. Figure 14(a) shows the results obtained under the test condition (A) in Table 3, and Figure 14(b) shows the results obtained under the test conditions (B). In both conditions, the larger root (R), the occurrence of edge crack was suppressed. Under the test condition (A), edge crack occurred even in the specimen with the U shaped grooves with R 0.65mm and 0.95mm, but it was a minor one that was not judged as an invalid in accordance with NACE TM0177-2016 and the edge cracks were reduced compared with those in the standard V shaped side groove with R 0.25mm. Under the test condition (B), edge crack did not occur in the U shaped groove with R 0.95mm. Figure 15 shows the comparison of the K_{Issc} values obtained using each specimens under the test conditions (A) and (B) in Table 3. Under both test conditions, there was no significant difference in the K_{Issc} values using each test piece.



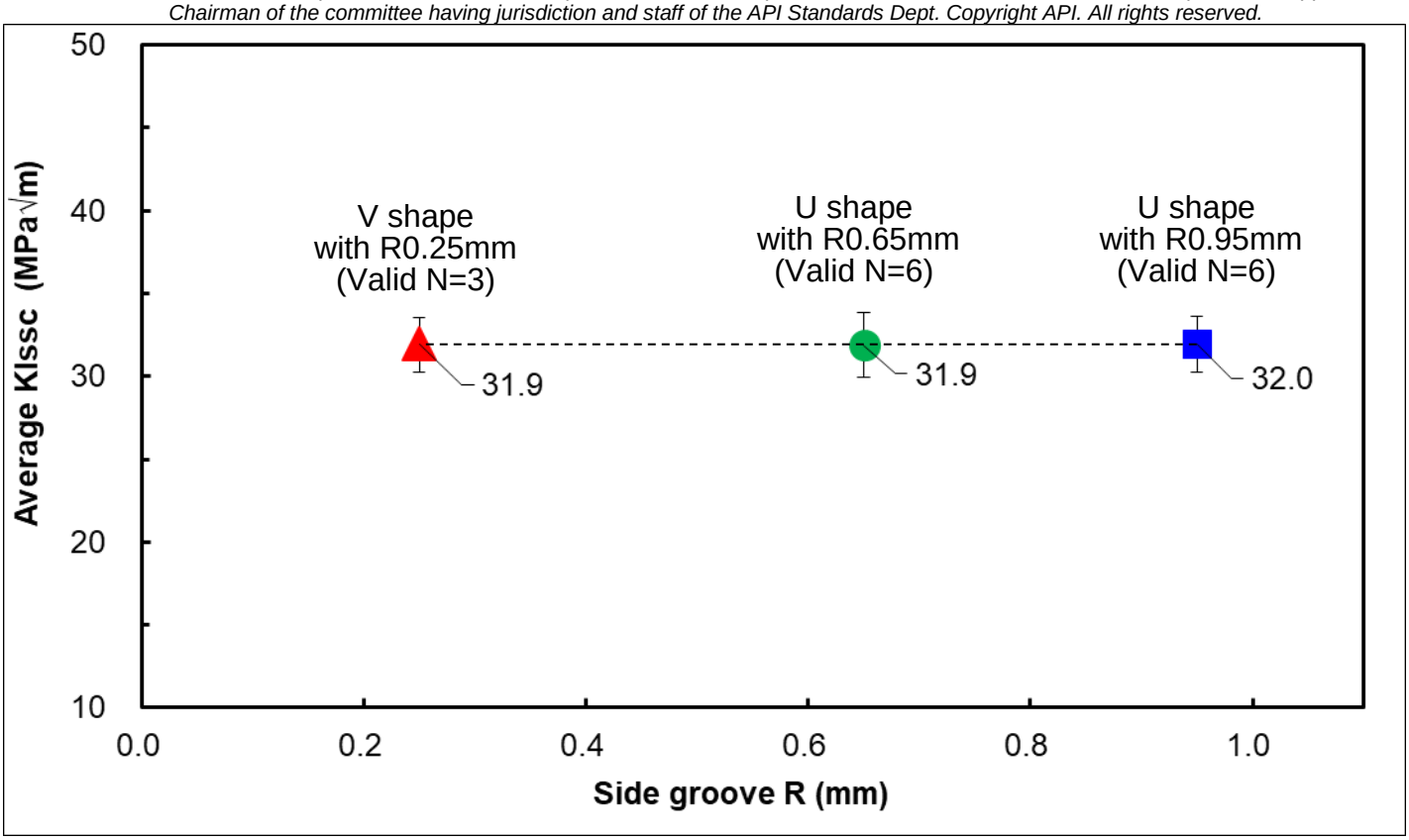


(a) Results obtained under test condition (A) in Table 3

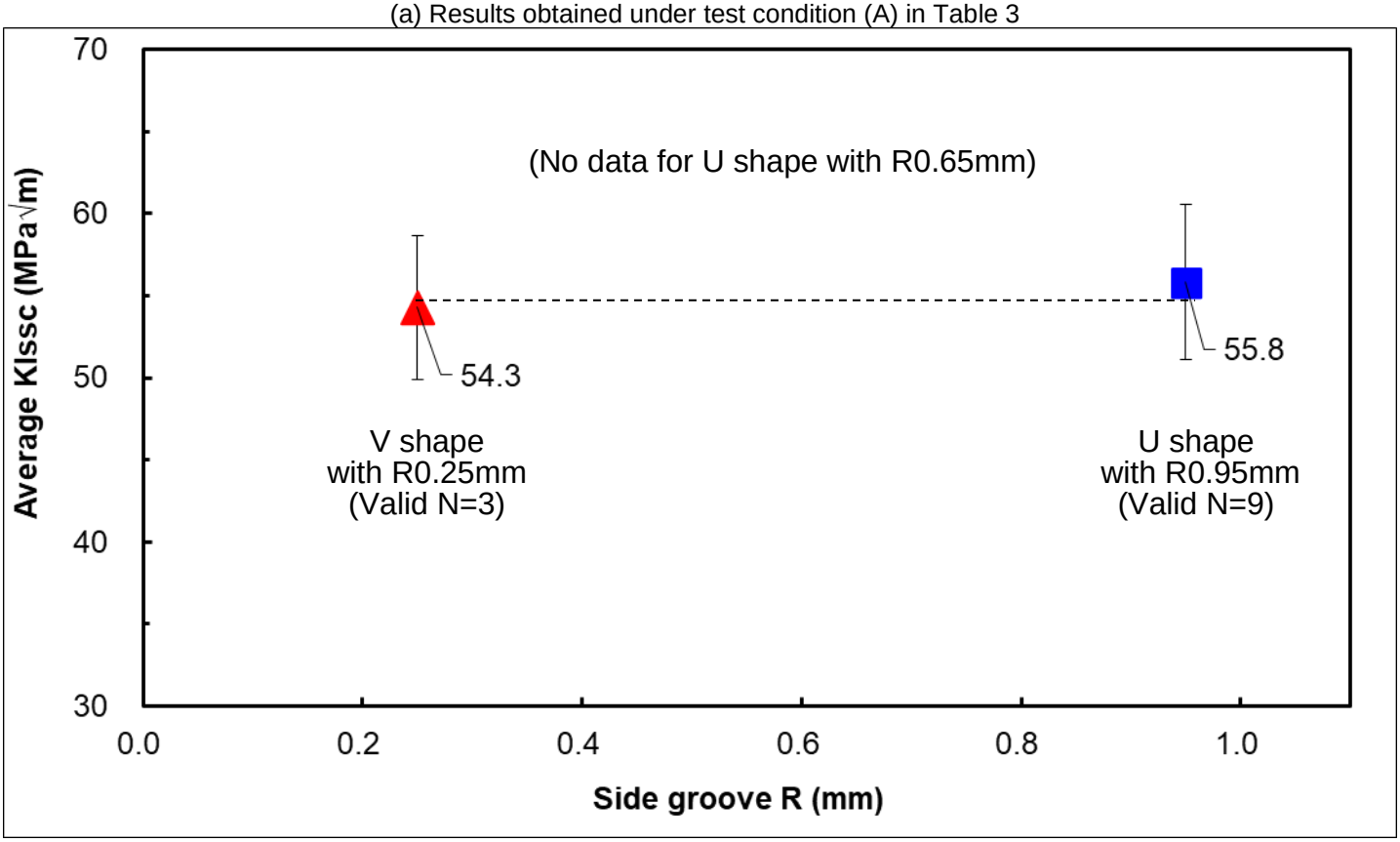


(b) Results obtained under test condition (B) in Table 3

Figure 14—Comparison of total length of Edge Crack



(a) Results obtained under test condition (A) in Table 3



(b) Results obtained under test condition (B) in Table 3

Figure 15—Comparison of K_{Issc} values obtained from specimens with validity of crack (SSC) growth

Photo 1 shows a comparative example of the crack (Sulfide Stress Cracking) growth surface after the test under the condition (A) and (B) in Table 3. In the standard V shaped groove with R0.25mm, the crack at bottom of the groove propagated longer, and the crack tip after the test showed the characteristic of concave for the propagation direction. On the other hand, the crack tip of the U shaped groove with R0.95mm showed a characteristic of uniform over the width of the side groove. In this test, the non-planar crack surface specified in NACE TM0177-2016 standard was not observed.

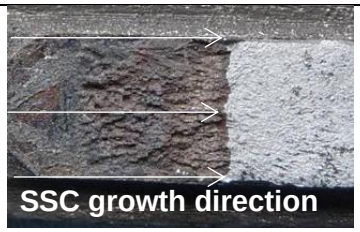
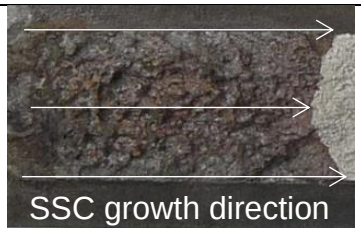
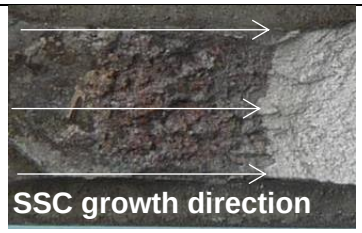
	V shape side groove with R0.25mm	U shaped side groove with R0.95mm
Test condition (A) in Table 4		
Test condition (B) in Table 4		

Photo 1—Comparison of fracture surface after DCB testing

3 Optimization of side-groove configuration

The optimization of the U shaped groove was considered in this chapter. The U shaped groove is optimized from the both points of reducing both edge cracks and non-planar fracture surface. Here, for C110 in 1 bar H_2S-saturated NACE Sol. A**,** the occurrence of edge crack and non-planar fracture surface between U grooves with R0.65 and with R0.95 was discussed.

3.1 Testing Material

C110 material manufactured by Company A as a test material was used. Table 5 shows the pipe size and mechanical properties. The chemical composition is shown in Table 6.

Table 5—Pipe size and mechanical properties

Material	Outer Diameter (mm)	Wall Thickness (mm)	Yield Strength (ksi)	Tensile Strength (ksi)	HRC (mid-wall)
C110	311.15	28.58	116.2	125.0	26.8

Table 6—Chemical composition (mass %)

C	Mn	P	S	Cr	Mo
0.27	0.42	0.010	0.0010	1.03	0.69

3.2 Methodology

3.2.1 DCB test procedure

DCB test condition is shown in Table 7. In this investigation, pre-cracked DCB specimens with standard V shaped groove with R0.25mm, U shaped grooves with R0.65mm and R0.95mm were used.

Table 7—DCB test condition

Test method	NACE TM 0177 Method D		
Specimen size	Standard size Chevron notch + pre-crack (Crack start position 33.75mm)		
Wedge material	As quenched material		
Wedge insertion	Vise method		
Test Solution	NACE solution A		
Test gas	1 bar H_2S		
Test solution initial pH	2.7		
Test duration	336hr		
Target arm displacement	0.51mm		
Stirring rate in test solution	100rpm with magnetic stirrer		
Temperature control	24(+/-1.0) ^{o}C		
Test frequency	V shaped groove with R0.25mm N=6	U shaped groove with R0.65mm N=6	U shaped groove with R0.95mm N=6

3.3 Results

3.3.1 Results of DCB testing

Table 8 shows the results of DCB testing for each shaped groove for C110 in 1 bar H_2S-saturated NACE Sol. A**.** Using those data, the occurrence of edge crack was compared in Figure 16 and Figure 17 shows the comparison of K_{Issc} values among each shaped groove. For the standard V shaped groove with R0.25mm, the invalid results were occurred. Compared to the V shaped groove, the occurrence of edge crack was suppressed for the U shape grooves with R0.65mm and R0.95mm.

Although the U shaped groove with R0.95mm is likely the most suitable configuration to prevent the occurrence of edge crack, small difference in the occurrence of edge crack between U grooves with R0.65mm and R0.95mm. As shown in Figure 18, in terms of preventing both edge crack and non-planar fracture surface, R0.65mm is suitable. For this condition (C110 in 1 bar H_2S-saturated NACE Sol. A), there were not remarkable differences in K_{Issc} values among each shaped groove.

Table 8—Results of DCB testing

Notch type	Side-groove	TP No.	Fatigue Crack Length	Initial Crack Length	Measured Arm Displacement	K_{Issc} ksi√inch		Hardness from test specimens	Remarks
			(mm)	(mm)	(mm)	Each	Avg.		
Chevron notch + pre-crack	V shape with R0.25 mm	A-1	2.00	33.79	0.516	27.4	29.0	26.1	-
		A-2	2.00	33.79	0.519	29.4		27.0	-
		A-3	2.00	33.87	0.517	30.3		25.9	-
		A-4	2.00	33.86	0.519	31.9		26.4	e’
		A-5	2.00	33.76	0.519	27.0		25.9	e
		A-6	2.00	33.79	0.511	28.4		25.7	e
Chevron notch + pre-crack	U shape with R0.65 mm	A-13	2.00	33.81	0.515	29.4	28.3	26.7	e’
		A-14	2.00	33.81	0.518	30.8		26.5	-
		A-15	2.00	33.85	0.516	28.5		26.8	-
		A-16	2.20	34.01	0.516	29.1		27.2	-
		A-17	2.00	33.82	0.519	25.6		26.6	
		A-18	2.10	33.98	0.519	27.7		26.7	-
Chevron notch + pre-crack	U shape with R0.95 mm	A-7	2.00	33.86	0.514	27.6	29.1	27.0	-
		A-8	2.00	33.87	0.517	29.8		27.1	-
		A-9	2.00	33.84	0.514	31.8		27.0	-
		A-10	2.00	33.74	0.520	28.1		26.9	-
		A-11	2.00	33.76	0.515	28.4		27	-
		A-12	2.00	33.82	0.515	28.8		27	-

e: invalid due to edge crack
e’: invalid due to edge crack at the front of crack

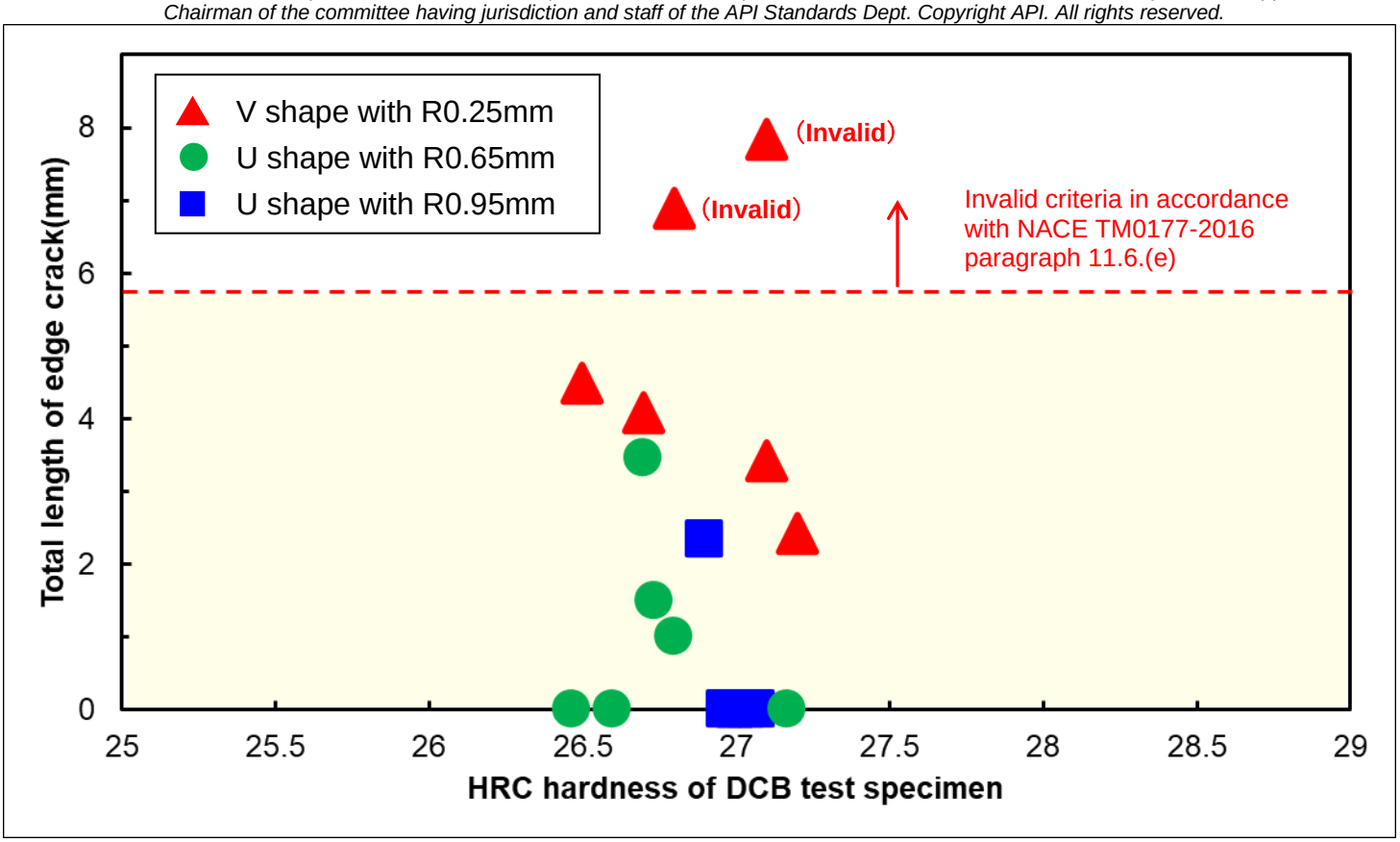


Figure16—Comparison of occurrence of edge crack

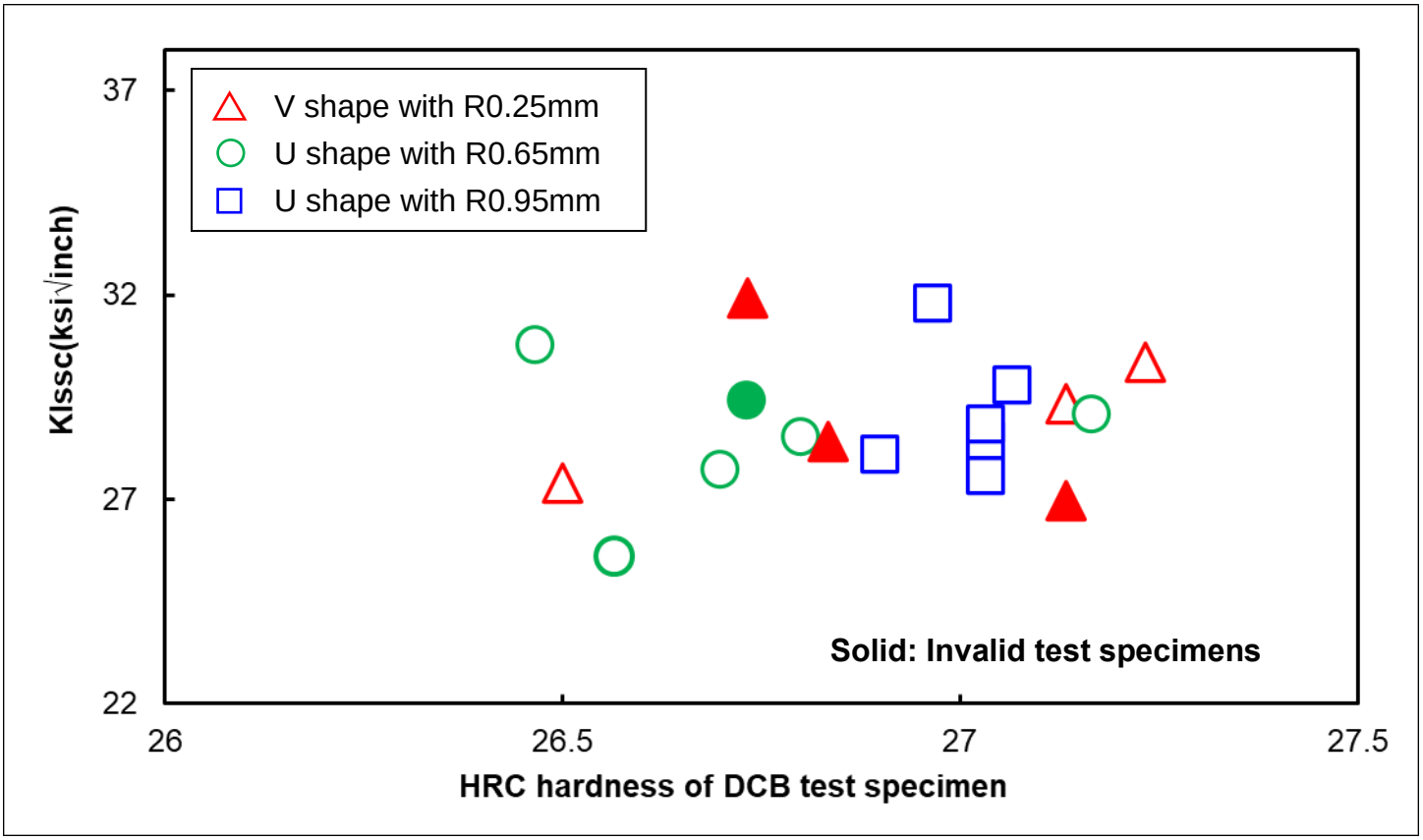


Figure 17—Comparison of K_{Issc} values

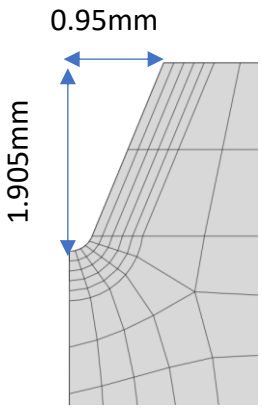
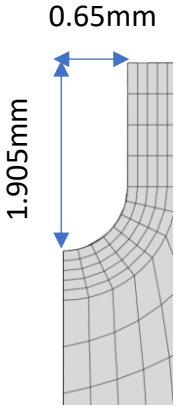
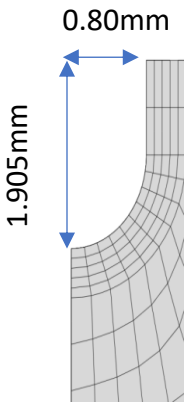
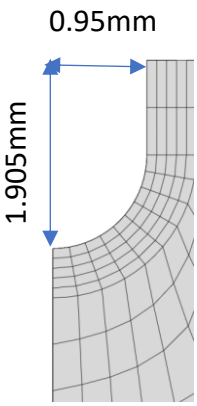
Side-groove	(a) V shape with R0.25mm	(b) U shape with R0.65mm	(c) U shape with R0.80mm	(d) U shape with R0.95mm
Configuration				
Remarks	Standard in NACE TM0177-2016	**Stiffness: equal to standard V**	Intermediate	width : equal to standard V
Fracture surface	Planar			Non-planar
K value (edge crack)	High			Low

Figure 18—Optimization of side groove configuration for C110 in 1 bar H_2S-saturated NACE Sol. A

4 Verification using DCB specimens machined by third party

For further verification of the effect of the U shaped groove both on reducing edge crack and non-planar fracture surface for C110 in 1 bar H_2S-saturated NACE Sol. A, the investigation using DCB specimens machined by Third Party was conducted.

4.1 Methodology

4.1.1 Testing Material

In this investigation, C110 material manufactured by Company A (A) as a test material was used. Its pipe size and mechanical properties are shown in Table 9. Table 10 shows the chemical composition.

Table 9—Pipe size and mechanical properties

Material	Outer Diameter (mm)	Wall Thickness (mm)	Yield Strength (ksi)	Tensile Strength (ksi)	HRC (mid-wall)
C110	250.8	17.8	114.4	124.4	27.0

Table 10—Chemical composition

C (mass%)	Mn (mass%)	P (mass%)	S (mass%)	Cr (mass%)	Mo (mass%)
0.26	0.42	0.008	0.0011	1.04	0.73

4.1.2 Specimen machining

As shown in Table 11, DCB specimens with V shape groove with R0.25mm and U shaped grooves with R0.65mm and R0.95mm were machined both by Third party and Company A (A) to investigate whether effect of U shaped side groove can be confirmed using both specimens.

Table 11—Evaluation program

	Process			
	Sample	**Machining DCB specimen with fatigue pre-crack** • V shaped groove with R0.25mm • U shaped groove with R0.65mm • U shaped groove with R0.95mm	**DCB testing**	**Fracture surface evaluation**
Test #1	API 5CT C110 (same pipe)	Company A (A)	→A	→A
Test #2		Third party [Their procedure]	→A	→A

At third party laboratory, procedure of pre-cracking was confirmed to be in accordance with the third party laboratory's protocol ~~as discussed in advance by API SC 5 WI 2413 (DCB side groove study)~~.

- Step1: 321lbf for 180,000 cycles (321lbf corresponds to 18.6 ksi$\sqrt{in}$)
- Sharpening: 214lbf for 20,000 cycles

All verifications of validation of specimens were conducted in accordance with NACE TM0177-2016.

4.1.3 NACE Method D test

DCB tests were implemented for C110 in 1 bar H_2S-saturated NACE Sol. A in accordance with NACE TM0177-2016. Table 12 shows the testing condition.

Table 12—DCB test condition

Specimen size	Standard size, • V shape side-groove (R0.25mm) • U shaped side-groove (R0.65mm) • U shaped side- groove (R0.95mm)
Wedge material	As quenched material
Test Solution	5.0%NaCl+0.5%CH_3COOH
Test gas	1 bar H_2S
Test solution initial pH	between 2.6 and 2.8
Test duration	336 hours
Target arm displacement	0.51mm (+/-0.03)
Temperature control	24(+/-1.0) ^{o}C

4.2 Results

4.2.1 Result of Test #1 (machining: Company A→DCB testing: Company A→Fracture surface evaluation: Company A

Table 13 shows the results of Test #1 for each shaped groove. Figure 19 shows the comparison of the occurrence of edge crack between the V shaped groove with R0.25mm and the U shaped groove with R0.65mm. The validation of mechanical aspects of this DCB testing was confirmed by compliance curve evaluation in Figure 20.

Following results were obtained.

a) “Non-planar surface” was not observed.

b) The occurrence of edge crack was suppressed by U shaped groove with R0.65mm

c) There are no significant differences in K_{Issc} values.

Table 13—Results for Test #1
(Machining: Company A→DCB testing: Company A→Fracture surface evaluation: Company A)

V shaped groove (R:0.25mm)					U shaped groove (R:0.65mm)			
ID	Hardness	K_{Issc} (ksi√inch)		Combined width of edge cracks (mm)	Hardness	K_{Issc} (ksi√inch)		Combined width of edge cracks (mm)
		Ind.	Ave.			Ind.	Ave.	
1	26.0	28.78	27.42	3.44	26.3	26.50	27.39	0
2	26.1	28.48		4.06	26.4	25.75		0
3	25.9	28.71		4.18	25.9	29.45		0
4	26.1	26.33		2.32	26.2	24.67		0
5	26.8	24.71 *		**9.14**	26.8	27.32		0
6	26.3	30.02 *		**5.94**	26.9	24.68		0
7	26.5	27.34		2.54	27.1	28.52		0
8	26.7	27.83		2.25	26.8	28.68		1.90
9	26.5	27.33		1.45	26.4	24.16		0
10	26.7	28.08		3.07	26.0	30.87		0
11	26.5	27.70		2.23	26.4	29.50		0.52
12	26.5	28.81		5.41	26.4	28.63		0

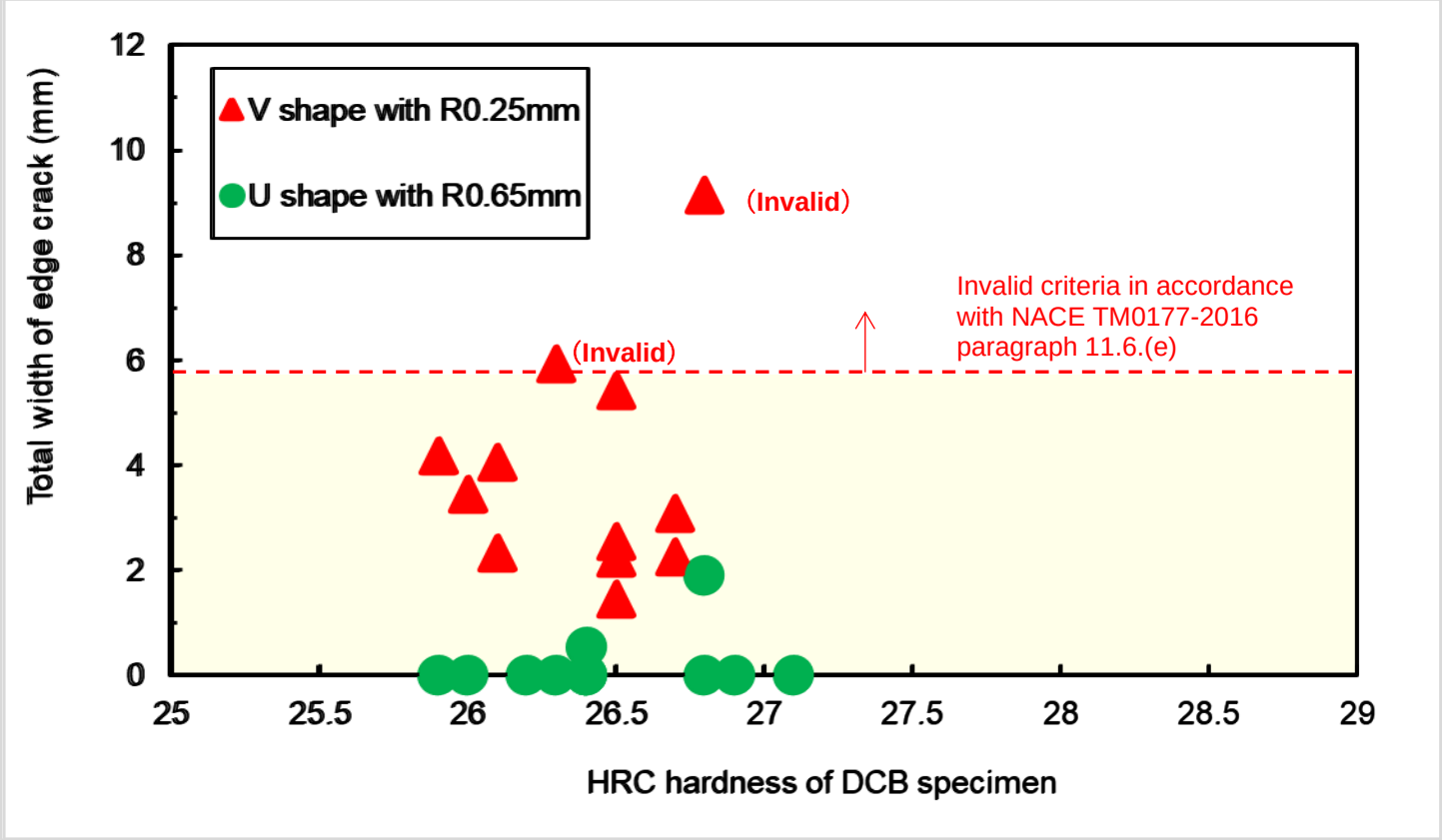


Figure 19—Comparison of edge crack width for Test #1

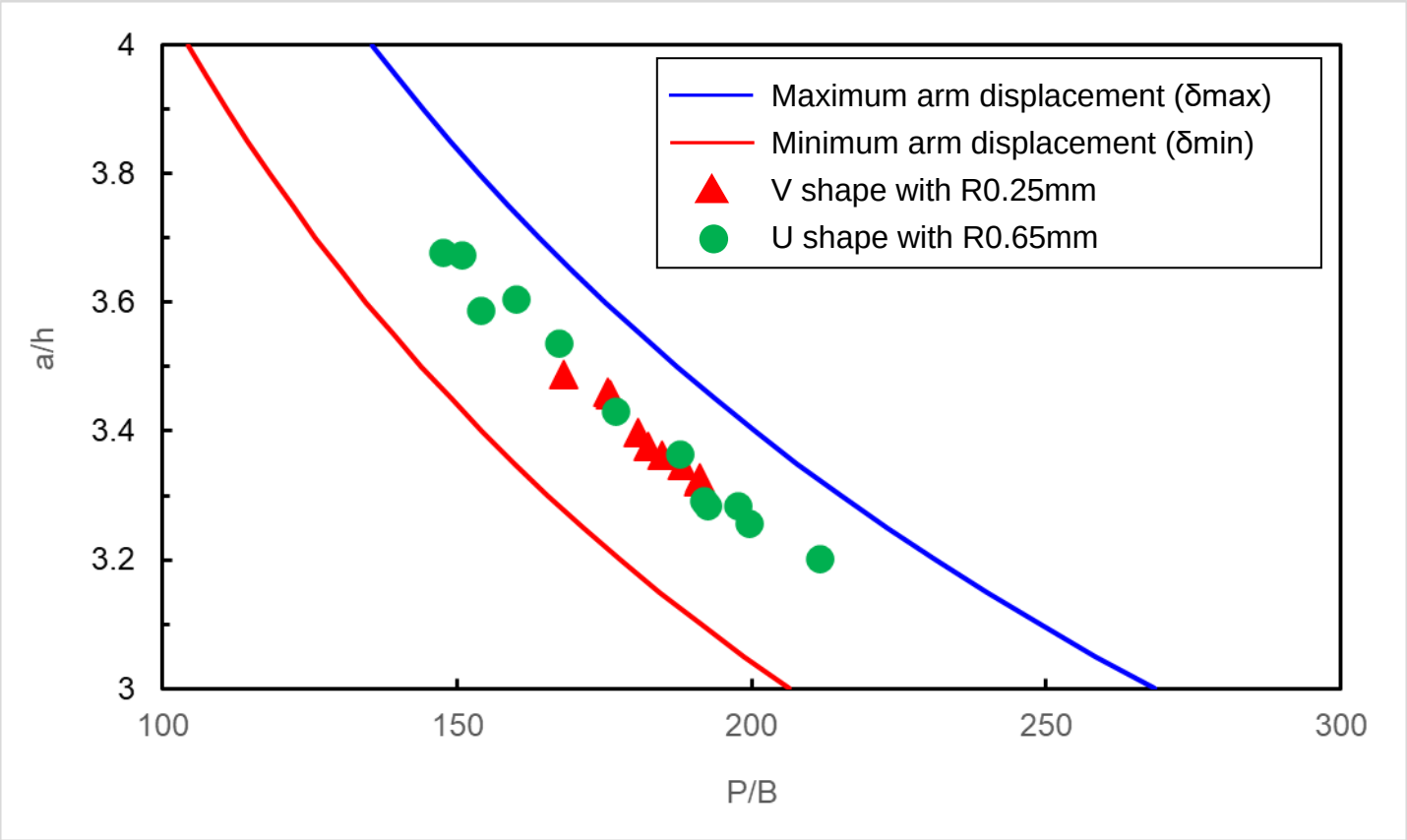


Figure 20—Compliance curve for Test #1

4.2.2 Results of Test #2 (machining: Third party→DCB testing: Company A→Fracture surface evaluation: Company A)

Table 14 shows the DCB testing results of Test #2 for each shaped groove. Figure 21 shows the comparison of the occurrence of edge crack among the V shaped side groove with R0.25mm and the U shaped side grooves with R0.65mm and R0.95mm. The validation of mechanical aspects of this DCB testing was confirmed by compliance curve evaluation in Figure 22.

Following results were obtained.

a) Nonplanar surface was not observed for all test specimens.

b) Remarkable edge crack was observed for one test specimen with the V shaped groove.

c) There were no significant differences in K_{Issc}

Table 14—Results for Test #2
(Machining: Third party→DCB testing: Company A→Fracture surface evaluation: Company A)

ID	Configuration of side groove	K_{Issc}		Hardness of DCB specimens	Total width of edge cracks (mm)
		Each	Avg.		
		ksi√inch			
292*	V shape with R0.25mm	28.4	29.3	26.7	**13.23**
293		29.8		26.6	4.00
294		29.2		26.1	2.03
295		29.9		26.7	3.13
296		28.1		25.9	2.23
332	U shape with R0.65mm	30.2	29.9	26.7	1.02
333		31.5		26.6	1.86
334		29.7		26.7	1.96
335		29.3		26.7	5.40
336		28.9		26.7	3.84
347	U shape with R0.95mm	29.9	28.0	26.7	1.43
348		31.2		26.1	0.00
349		26.9		26.9	3.62
350		27.1		26.7	4.77
351		28.1		26.7	0.00

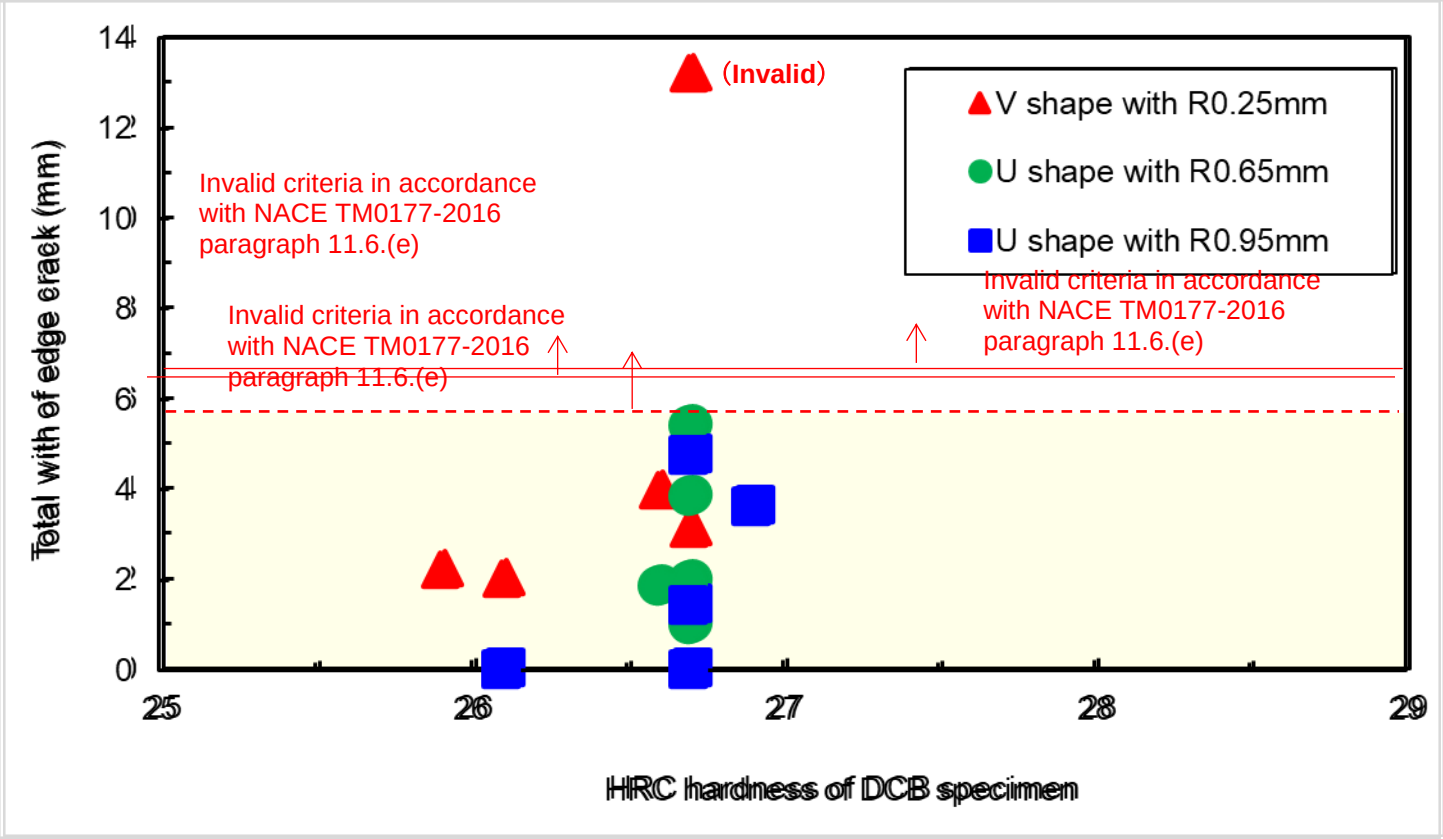


Figure 21—Comparison of edge crack width for Test #2

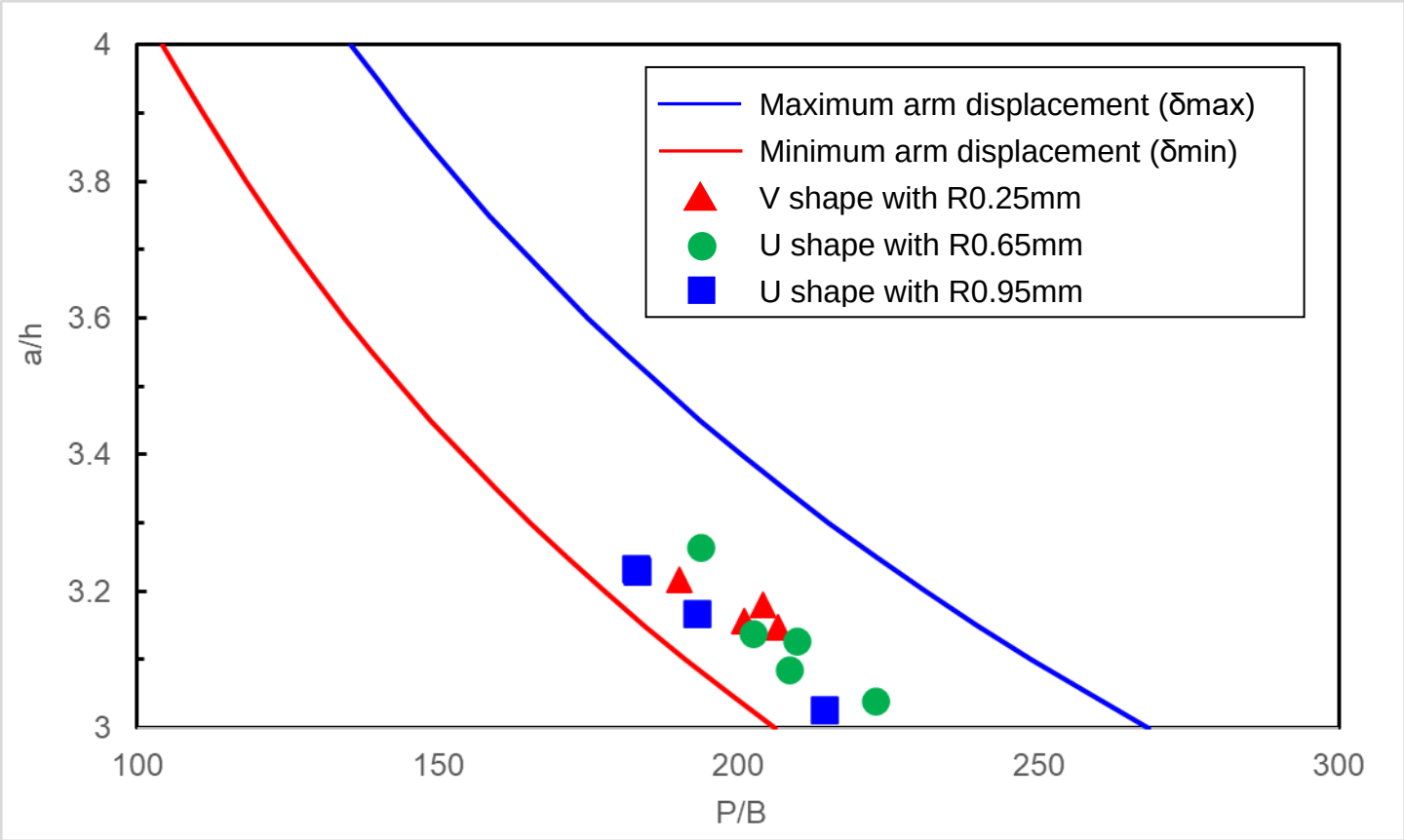


Figure 22—Compliance curve for Test #2

As summarized in Table 15, the effect of the U shaped side groove both on reducing edge cracking and non-planar surface for C110 in API 5CT standard condition was verified even when using specimens machined by Third party.

Table 15—Verification using DCB specimens machined by Third Party

Evaluation point	**Test #1** Machining: Company A DCB testing: Company A Fracture surface: Company A	**Test #2** Machining: Third party DCB testing: Company A Fracture surface: Company A
Planar/ Non planar	Planar surface	Planar surface
Edge crack	The U shaped grooves prevented the edge crack	The U shaped grooves prevented the edge crack
K_{Issc}	Comparable among the U grooves and the standard V shaped groove	Comparable among the U grooves and the standard V shaped groove

a) No effect of machining on the occurrence of non-planar surface

b) The U shaped grooves prevent the occurrence of edge crack

c) There is no significant difference in K_{Issc} between V groove and U groove

5 Complementary verification

~~In API WI2413 (DCB side groove study), the optimization of side groove configuration has been discussed.~~ Compared with the standard V shaped grooves with R0.25mm specified in NACE TM0177-2016, the beneficial effect of the proposed U shaped grooves on the suppression of edge crack was confirmed with the results using specimen machined respectively by Company A and Third party from the same C110 casing pipe sample in 1 bar H_2S-saturated NACE Sol. A. ~~To finalize, complementary verification required in API WI2413 (DCB side groove study) as shown in Table 16 was discussed.~~

Table 16—Complementary verification

#	Item
1	**Inspection of edge crack: (Please refer to Appendix (4))** For the standard V groove, severe edge-cracks has occurred, but it seemed not to affect its K_{Issc} value. Then, inspection of edge cracks conducted by API ~~WI2413 (DCB side groove study)~~TR 5DCB members was required.
2	**Machining effect** Machining effect among the standard V and the U shaped grooves was confirmed. Company A conducted EBSD analysis in order to evaluate distortion due to machining.
3	**Verification using heavy wall sample** Edge crack is likely to occur in heavy wall material (Coupling stock material) due to segregation.

5.1 Investigated Configurations of side groove

For this investigations, DCB specimens with the standard V shaped groove with R0.25mm, the U shaped grooves with R0.65mm and R0.95mm were evaluated.

5.2 Methodology

5.2.1 Inspection of edge crack

As shown in Appendix (4), Company A sent those phots of fracture surface to API WI2413 (DCB side groove study), inspections of edge-cracks were conducted in accordance with TM0177 and the procedure provided by one of API WI2413 (DCB side groove study) members.

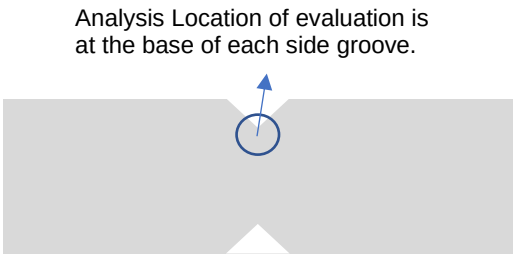


Figure 23—Location for EBSD analysis

5.2.2 Machining effects

Machining effects at the base of each side groove were analyzed by EBSD as shown in Figure 23. The analyzed area was 100μm x 100μm and step size is 0.1μm. The machining effects was compared using Kernel Average Misorientation (KAM).

Regarding evaluation of machining effect with KAM value by EBSD:

In this investigation, influence of the machining at the bottom of side groove among the standard V and the proposed U grooves was evaluated by KAM value by EBSD, which defined an average misorientation around a pixel with respect to a defined set of adjacent neighboring points.

According to following two literatures as example, KAM was considered to be indirectly related to the deformation strain or dislocation density.

1) "Dislocation densities and intergranular stresses of plastically deformed austenitic steels, Material Science & Engineering A 743 (2019) 32-39.

In this literature, the < hkl > dependence of dislocation density obtained by convolutional multiple whole profile fitting (CMWP) for Neutron Diffraction (ND) measurement is similar to the KAM value distribution.

2) "Influence of microstructural heterogeneity and plastic strain on geometrically necessary dislocation structure evolution in single-phase and two-phase alloys", Materials Characterization 170 (2020) 110690

In this literature, EBSD is used to quantify evolution of the generation of geometrically necessary dislocations (GND) content by KAM map in three different steels. Strong correlation between KAM and GND was shown.

5.2.3 Verification using heavy wall sample

5.2.3.1 Testing Material

API 5CT C110 material manufactured by Company A as a test material was used for this investigation. Table 17 shows the pipe size and mechanical property of the C110 material. The chemical compositions were shown in Table 18.

Table 17—Pipe size and mechanical properties

Material	Size		Tensile test		HRC hardness								
					outside			Mid-wall			inside		
	O.D. (mm)	W.T. (mm)	YS (ksi)	TS (ksi)	1	2	3	4	5	6	7	8	9
C110	298.40	39.42	113.9	124.3	25.3	25.1	25.0	25.7	25.3	25.8	24.3	24.0	25.2

Table 18. Chemical composition (mass %)

C	Mn	P	S	Cr	Mo
0.25	0.46	0.007	0.001	1.01	0.70

5.2.3.2 DCB testing condition

Table 19 shows the DCB testing condition. API standard condition for API C110 with heavy wall thickness was applied for this investigation.

Table 19—DCB testing condition

Specimen size	Standard size with fatigue pre-cracked Chevron notch with V shaped groove with R0.25, U shaped grooves with R0.65,0.95
Wedge material	As quenched material
Wedge insertion	Vice method
Test Solution	NACE solution A
Test gas	1 bar H_2S
Test solution initial pH	2.7
Test duration	336 hours
Target arm displacement	0.51(+0.03/-0.05) mm
Stirring rate in test solution	100rpm with magnetic stirrer
Temperature control	24±1.7 ^{o}C

5.3 Results

5.3.1 Results of EBSD analysis

Figure 25 shows the results of EBSD analysis and the comparison of average KAM at the base of each shaped groove. There is no significant differences in the KAM among the different side grooves.

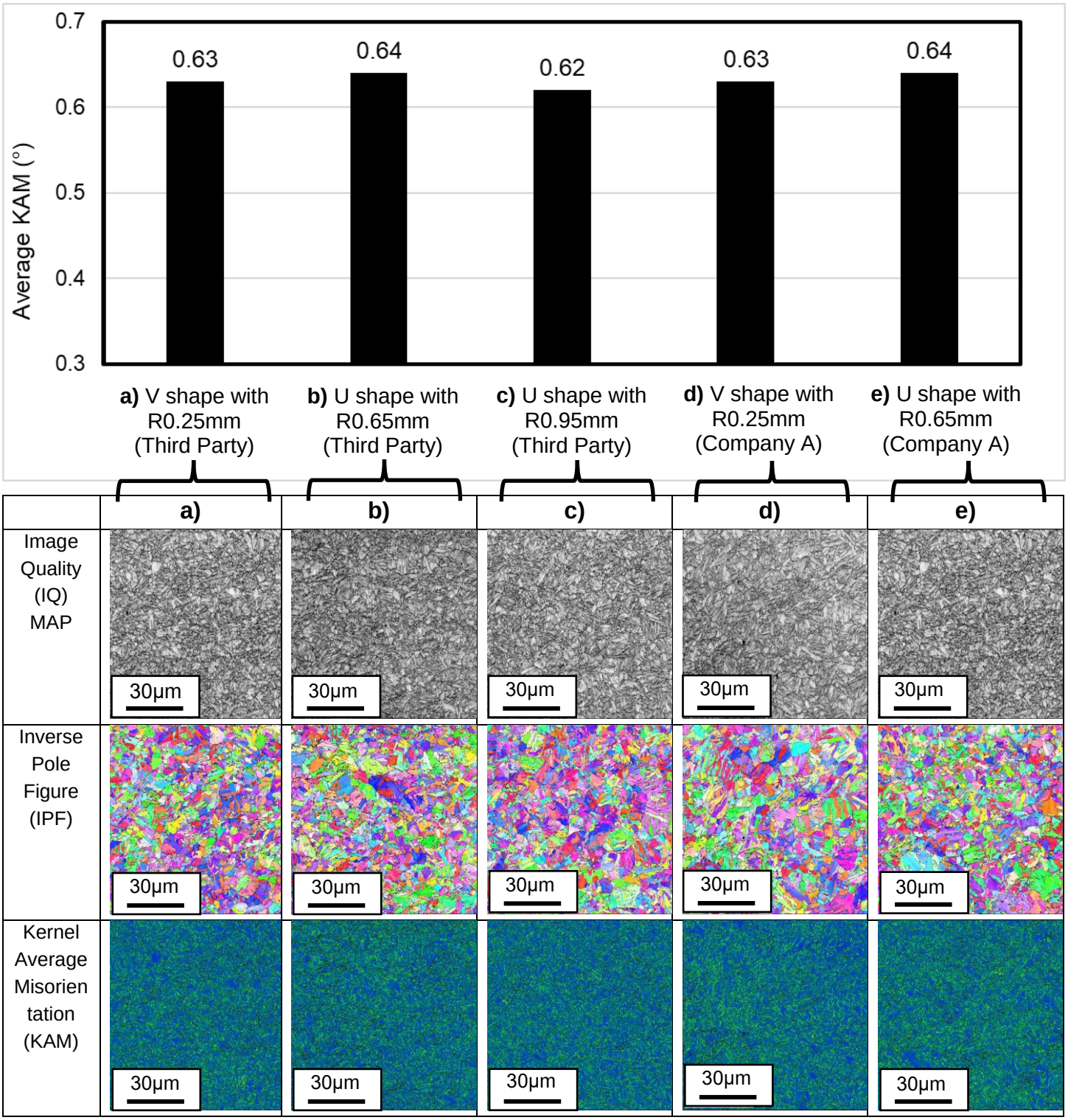


Figure 25—Comparison of KAM at the base of each side groove

5.3.2 Results of DCB testing

Tables 20 to 22 show the DCB testing results for each shaped groove. Using those data, the occurrence of edge crack and K_{Issc} values was compared in Figure 26 and Figure 27. As shown in Figure 26, invalid ratio of testing results by edge crack was reduced for the U shaped grooves. In addition, total width of edge crack was suppressed by applying the U

shaped grooves. Regarding K_{Issc} as shown in Figure 27, there is no significant difference among those specimens. The validity of mechanical aspects was confirmed by compliance curve evaluation in Figure 28. In Appendix (5), the photos of fracture surface were shown.

Table 20—Results of DCB testing for the V shaped groove with R0.25mm

ID	Configuration of side groove	K_{Issc}		Hardness from test specimens	Width of edge crack(mm)			Validity (11.6.1)
		Each	Avg.		①	②	total	
		ksi√inch						
QPT1-1	V shape With R0.25mm	28.2	29.1	27.2	0	0	0	Valid
QPT1-2		29.3		26.7	0	4.96	4.96	Valid
QPT1-3		29.3		26.4	0	3.78	3.78	Valid
QPT1-4		29.7		26.2	0	2.84	2.84	Valid
QPT1-5		29.4	28.9	26.1	2.61	3.29	5.9	Invalid (e)
QPT1-6		30.0		26.1	0	1.16	1.16	Valid
QPT1-7		29.1		26.0	0	6.23	6.23	Invalid (e)
QPT1-8		27.9		25.8	0	2.42	2.42	Valid
QPT1-9		29.1	27.4	26.1	0	0	0	Valid
QPT1 -10		27.4		26.4	1.17	1.53	2.7	Invalid (e)
QPT1 -11		22.9		26.1	0	0	0	Valid
QPT1 -12		30.1		26.2	0	4.32	4.32	Valid

e: Invalid fracture surface due to edge crack

①: Combined width of any crack front

②: Edge cracks lying away from the crack front that formed earlier in the test

Table 21—Results of DCB testing for the U shaped groove with R0.65mm

#	Configuration of side groove	K_{Issc}		Hardness from test specimens	Width of edge crack(mm)			Validity (11.6.1)
		Each	Avg.		①	②	total	
		ksi√inch						
QPT2-1	U shape with R0.65mm	29.9	29.7	26.2	0	0	0	Valid
QPT2-2		30.3		26.0	0	2.08	2.08	Valid
QPT2-3		27.9		26.4	0	0	0	Valid
QPT2-4		30.8		26.5	0	0	0	Valid
QPT2-5		26.9	29.4	26.3	0	0	0	Valid
QPT2-6		29.9		26.1	0	0	0	Valid
QPT2-7		30.3		26.1	0	0	0	Valid
QPT2-8		30.6		25.9	0	0.47	0.47	Valid
QPT2-9		27.5	29.7	26.2	0	0	0	Valid
QPT2-10		29.6		26.2	0	0	0	Valid
QPT2-11		33.6		26.4	0	0	0	Valid
QPT2-12		28.0		26.4	0	0	0	Valid

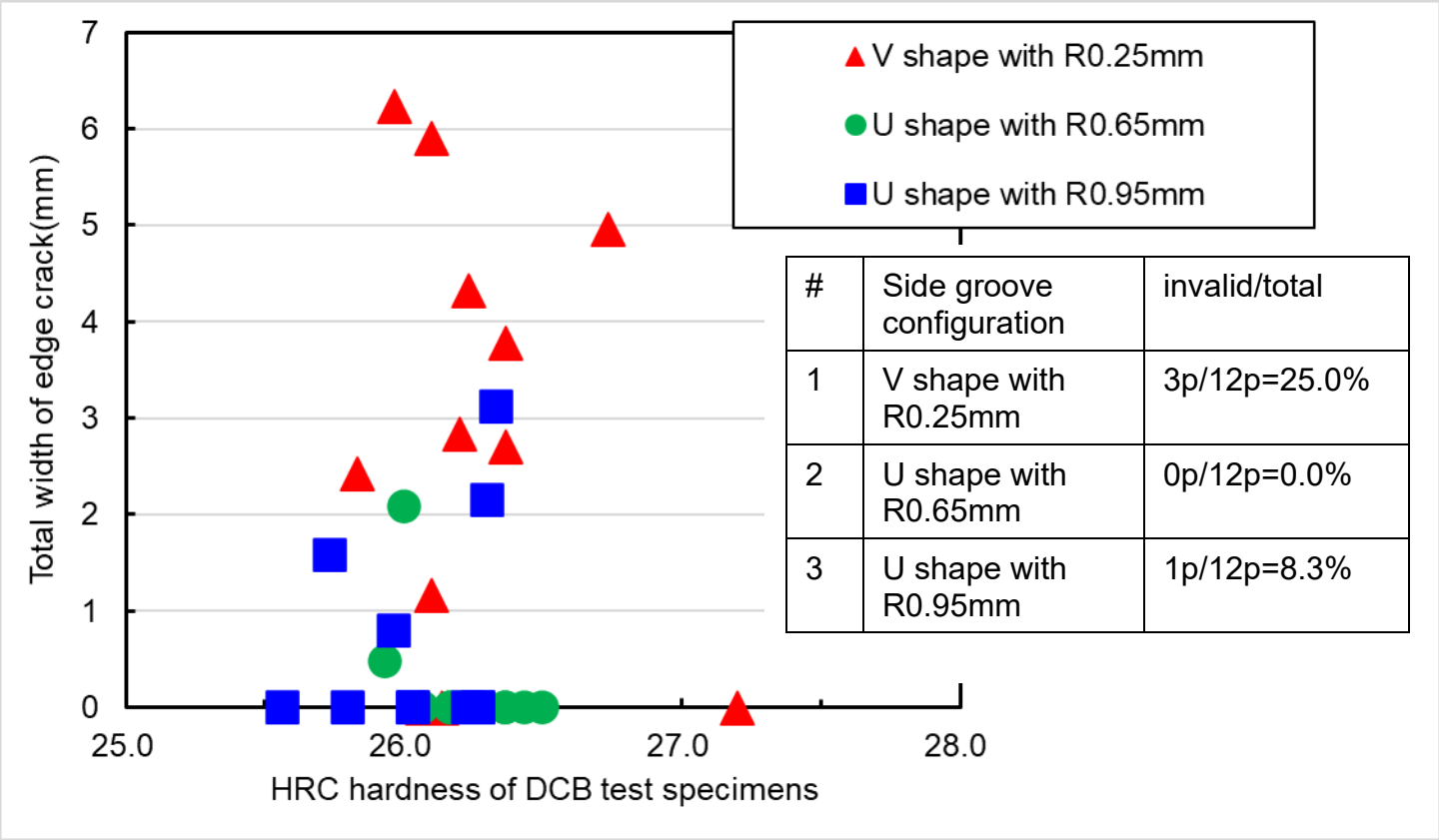
①: Combined width of any crack front

②: Edge cracks lying away from the crack front that formed earlier in the test

Table 22—Results of DCB testing for the U shaped groove with R0.95mm

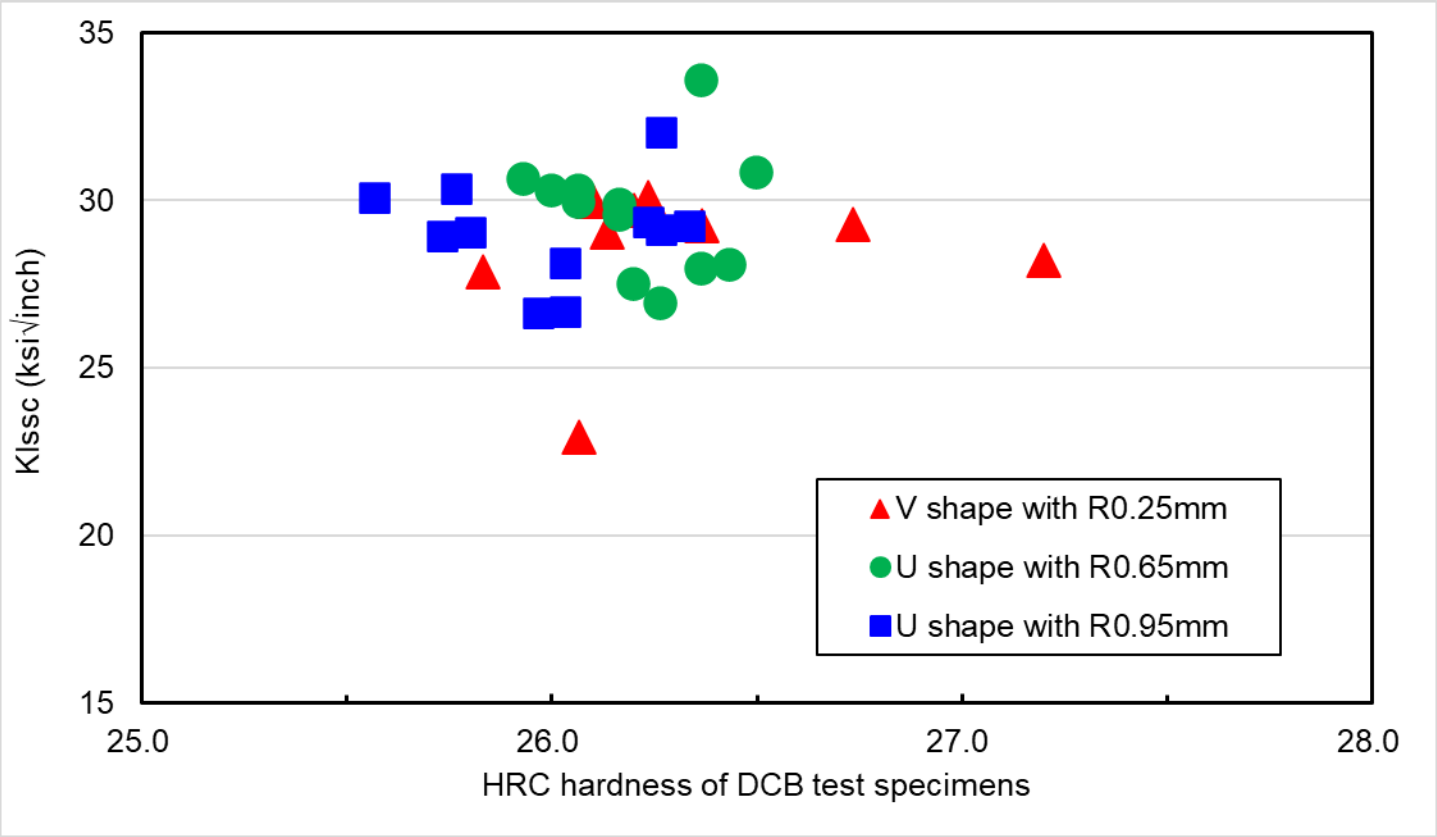
ID	Configuration of side groove	K_{Issc}		Hardness from test specimens	Width of edge crack(mm)			Validity (11.6.1)
		Each	Avg.		①	②	total	
		ksi√inch						
QPT3-1	U shape with R0.95mm	29.4	28.8	26.2	0	0	0	Valid
QPT3-2		29.2		26.3	0	3.12	3.12	Valid
QPT3-3		26.6		26.0	0	0.79	0.79	Valid
QPT3-4		30.1		25.6	0	0	0	Valid
QPT3-5		29.1	29.3	26.3	0	0	0	Valid
QPT3-6		29.8		26.3	2.14	0	2.14	Invalid (e)
QPT3-7		32.0		26.3	0	0	0	Valid
QPT3-8		26.7		26.0	0	0	0	Valid
QPT3-9		28.1	29.1	26.0	0	0	0	Valid
QPT3-10		29.1		25.8	0	0	0	Valid
QPT3-11		29.0		25.7	0	1.57	1.57	Valid
QPT3-12		30.3		25.8	0	0	0	Valid

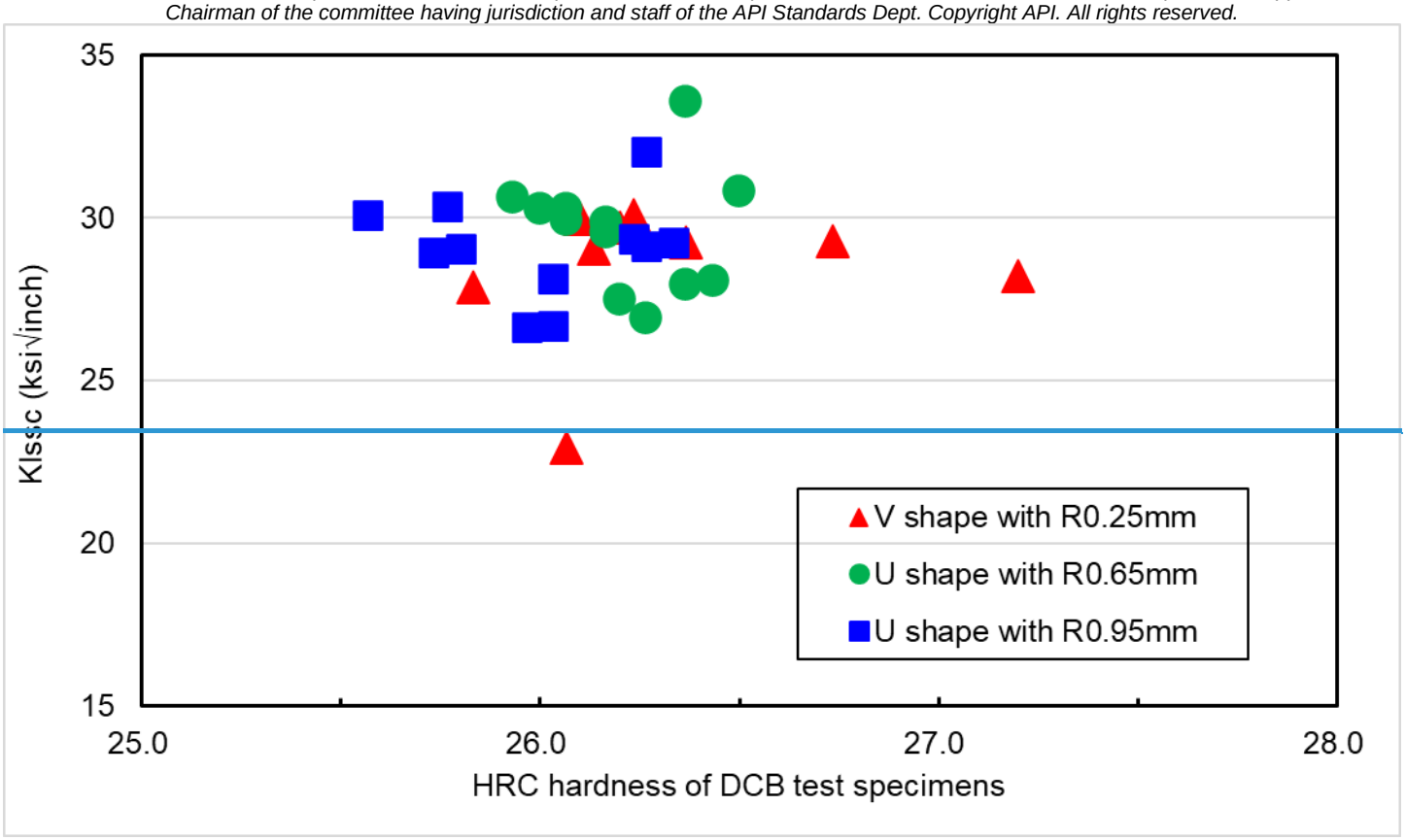
e: Invalid fracture surface due to edge crack
①: Combined width of any crack front
②: Edge cracks lying away from the crack front that formed earlier in the test



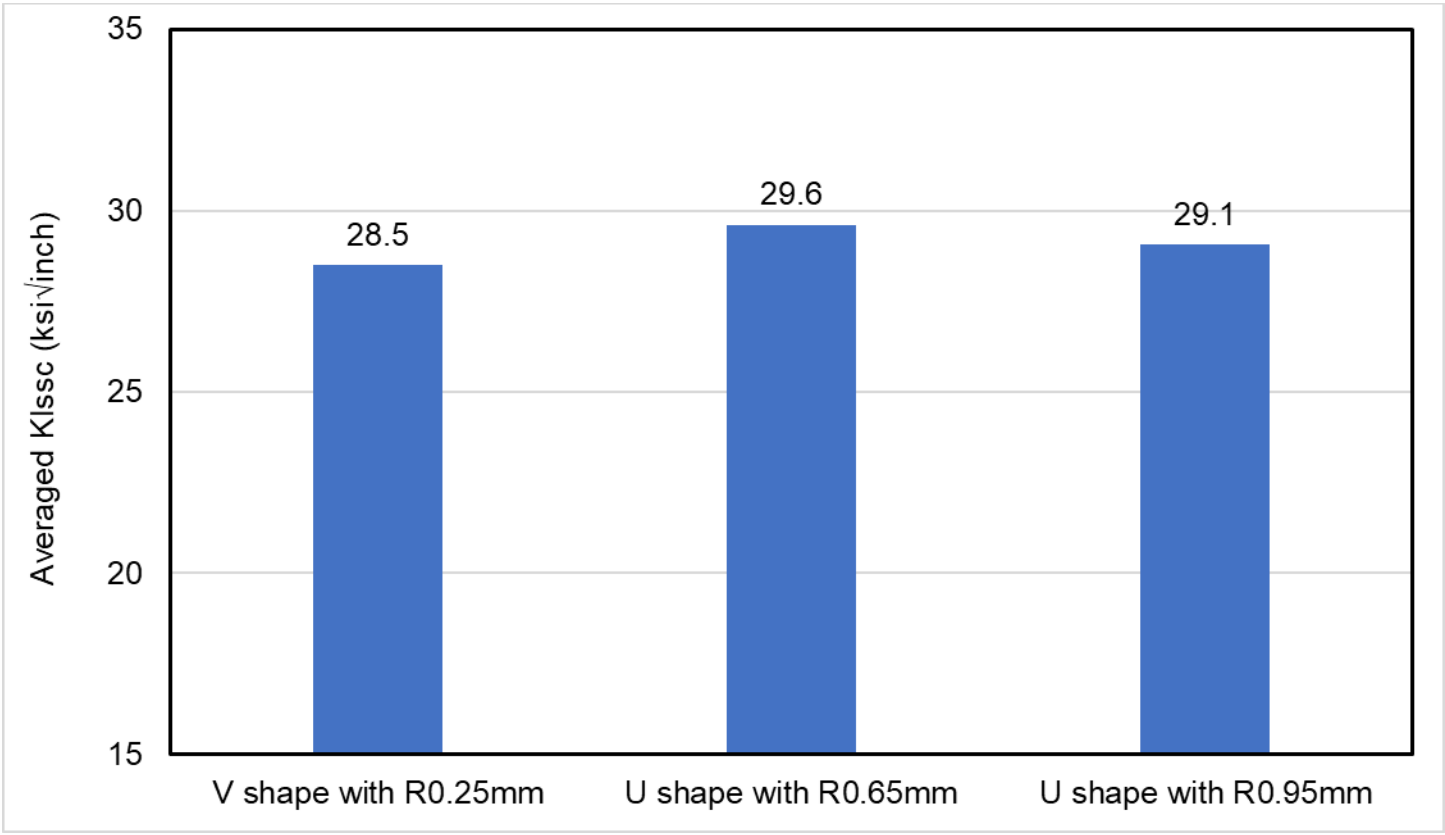
#	Side groove configuration	invalid/total
1	V shape with R0.25mm	3p/12p=25.0%
2	U shape with R0.65mm	0p/12p=0.0%
3	U shape with R0.95mm	1p/12p=8.3%

Figure 26—Comparison of invalidity ratio of testing results and the occurrence of edge crack





(a) Relationship between K_{Issc} and HRC hardness of DCB test specimen



(b) Comparison of average K_{Issc} for the different side grooves

Figure 27—Comparison of K_{Issc} among the different side grooves

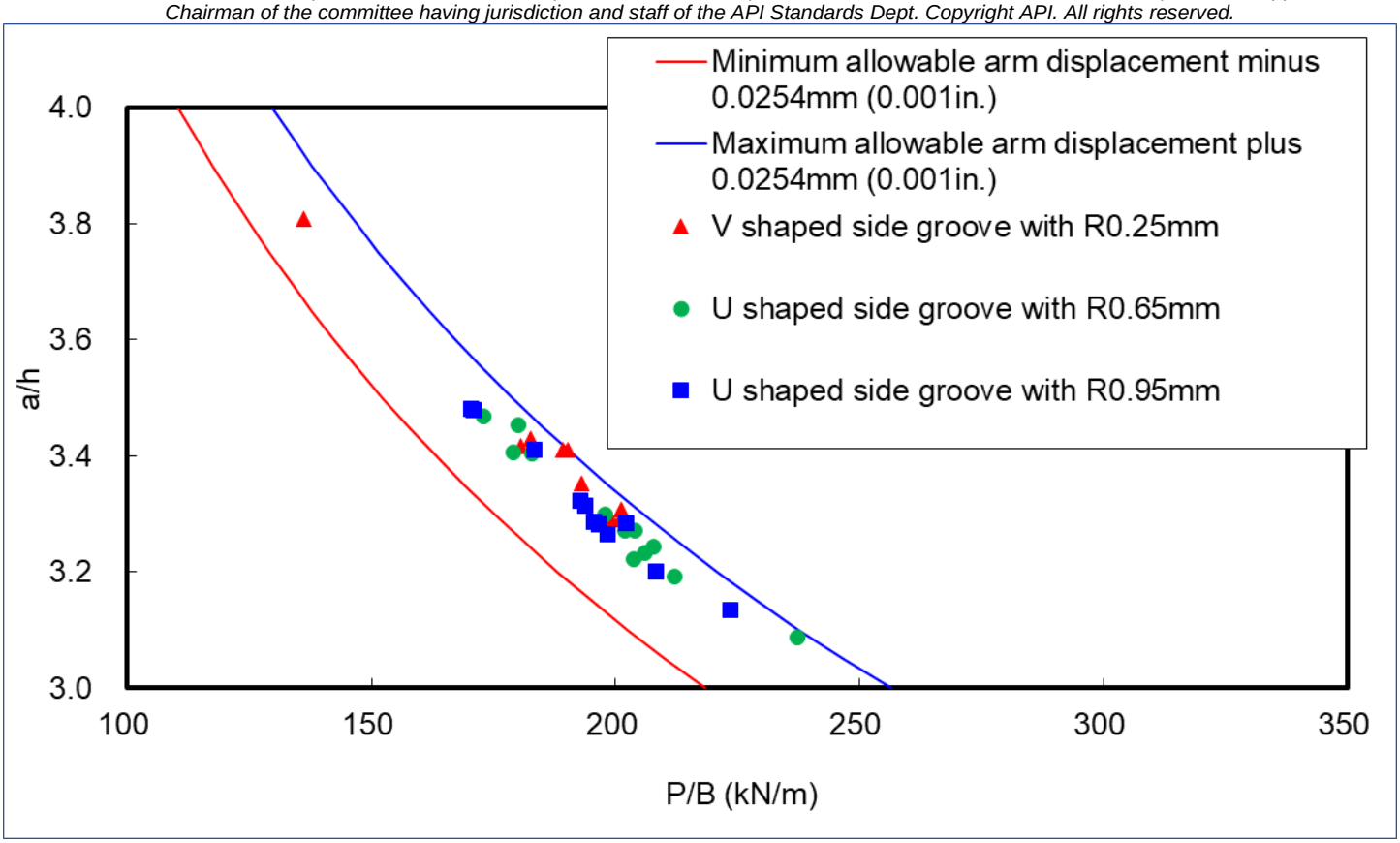


Figure 28—Compliance curve evaluation

As summarized in Table 23 for the complementary investigation, the U shaped grooves were verified for C110 in 1 bar H_2S-saturated NACE Solution A condition.

Table 23—Summary of the complementary verification

#	Item
1	**Inspection of edge crack:** It was verified that inspections of edge-cracks in the testing were in accordance with TM0177 & the procedure provided by one of API WI2413 (DCB side groove study) members.
2	**Machining effect:** No significant differences in KAM value by EBSD at the base of side groove were observed among the standard V shape groove with R0.25mm, the U shaped grooves with R0.65mm and R0.95mm.
3	**Verification using heavy wall sample:** The occurrence rate and total width of edge crack for API C110 Coupling stock material were reduced by applying the U shaped grooves with R0.65mm and R0.95mm compared with the standard V shaped groove with R0.25mm.

6 Conclusion

It is recommended to include the proposed U shaped groove with R0.65mm in NACE TM-0177 Method D as an option for Grade C110 to prevent the occurrence of edge crack for the following grade and test condition:

- API 5CT Grade C110

- 1 bar H_2S-saturated NACE TM0177 Solution A, standard size DCB specimen

For other grades and/or test environments other than Grade C110 in Solution A, it may be applicable if the effectiveness of U groove can be validated and documented.

API WI2413 (DCB side groove study) agreed to include the proposed U side-grooves as an option in NACE TM-0177 Method D. API WI2413 (DCB side groove study) will propose it to the AMPP committee (SC08).

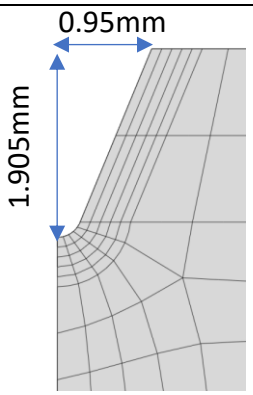
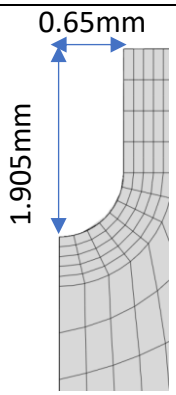
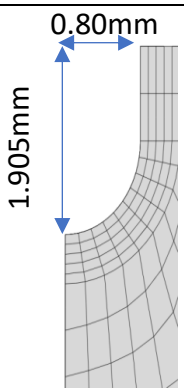
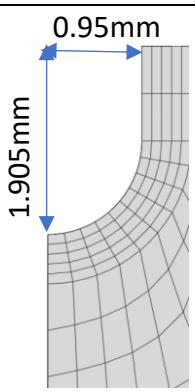
Side-groove	(a) V shape with R0.25mm	**(b) U shape with R0.65mm**	(c) U shape with R0.80mm	(d) U shape with R0.95mm
Configuration				
Remarks	Standard in NACE TM0177-2016	**Stiffness: equal to standard V**	Intermediate	width : equal to standard V
Fracture surface	Planar			Non-planar
K value (edge crack)	High			Low

Figure 29—Proposal for C110 in 1 bar H_2S-saturated NACE Sol. A

Remarks-1

The above points which have been discussed at API WI2413 (DCB side groove study) are also summarized in the AMPP (NACE) paper below. For further discussion, please see papers below.

- NACE 2016 paper no.7155
- NACE 2017 paper no.9102
- NACE 2018 paper no.11129
- NACE 2019 paper no.12842
- NACE 2021 paper no.16341
- AMPP 2023 paper no.19218

Remarks-2

For L80 as lower strength material, please see Appendix (1).
For mild sour conditions for C110 and C125 material, please see Appendix (2)
For comparison of effect of U side groove among two company, please see Appendix (3)
For fracture surface evaluation for inspection of edge crack in Sec. 5.2.1, please see Appendix (4)
For fracture surface evaluation for verification using C110 with heavy wall in Sec. 5.3.2, please see Appendix (5).

APPENDIX:

(1) Effect of U side grooves for L80 (Lower strength material)

The occurrence of edge crack was evaluated by DCB tests for lower strength material than C110.

For L80 material, DCB tests were conducted in order to ensure the crack propagation straightly when using the U shaped grooves.

Testing Material

The testing was performed using API 5CT L80 material manufactured by Company A as a test material as shown in Table 24. The chemical composition of the steel is shown in Table 25.

Table 24—Pipe size and mechanical properties

Material	size	Yield strength		Tensile strength		HRC Mid. wall
		MPa	ksi	MPa	ksi	
L80	OD244.48xWT13.84	627	90.9	743	107.8	20.4

Table 25—Chemical composition (mass%)

C	Mn	P	S	Cr	Mo
0.24	1.3	0.017	0.0038	0.21	0.01

Testing Method

Analysis of mechanical behavior of DCB test by FEA

As in the same method as in section 2.2.1, for L80 material, mechanical behavior of the DCB test specimen was calculated by FEA (Finite Element Analysis). The FEM analysis was conducted for the V shaped groove with R0.25mm and the U shaped groove with R0.95mm as elastic-plastic material with a stress-strain curve for L80 material.

DCB test condition

The DCB test according to NACE TM0177-2016 Method D was conducted as shown in Table 26 for L80 in 1 bar H_2S-saturated NACE Solution A. The test temperature in the vessels where the DCB specimens were placed was controlled to 24 +/-1.0°C by isothermal bath with circulating water during the test. The DCB specimens were set on a glass holder and electrically isolated. Target arm

displacement was set to 0.84mm, which is the nominal arm displacement in the middle of the allowable range for L80 in NACE TM0177. All DCB specimens were loaded by wedge insertion with appropriate thickness. The wedge was inserted by vice method. In case of the NACE TM0177 Solution A tests, specimens were exposed to the H_2S environment in the test solution for 14 days.

After exposure, the wedge was removed from the DCB specimen by using a tensile machine at a displacement rate of 0.5mm/min. The lift off load was determined at the abrupt change in the slope of the load versus displacement curve (“Lift-off” curve). After measuring lift-off load, the DCB specimen was chilled with liquid nitrogen and broken with a hammer and chisel to measure crack length at crack arrest. Then, the K_{Issc} values were calculated by Equation (1) as per NACE

TM0177 2016.

Table 26—DCB test condition

Testing method	NACE TM0177-2016, Solution A
Specimen size	Standard size • the standard V shaped groove • the U shaped groove (R0.95mm)
Wedge material	As quenched material
Wedge insertion	Vice method
Test Solution	5.0wt%NaCl + 0.5wt%CH_3COOH
Test gas	1 bar H_2S
Test solution initial pH	between 2.6 and 2.8
Test duration	336hr
Target arm displacement	0.84mm
Stirring rate in test solution	100rpm with magnetic stirrer
Temperature control	24(+/-1.0) ^{o}C

Results

Results of FEA

Figures 30 and 31 show the K value at center of the width and at bottom of the groove at the various crack length using the standard V shaped groove with R0.25mm and the U shaped groove with R0.95mm. The K value at center of the width of the U shaped groove is same as that of the standard V shaped groove. On the contrary, the K value at bottom of the U shaped groove is small as compared to a conventional V side-groove.

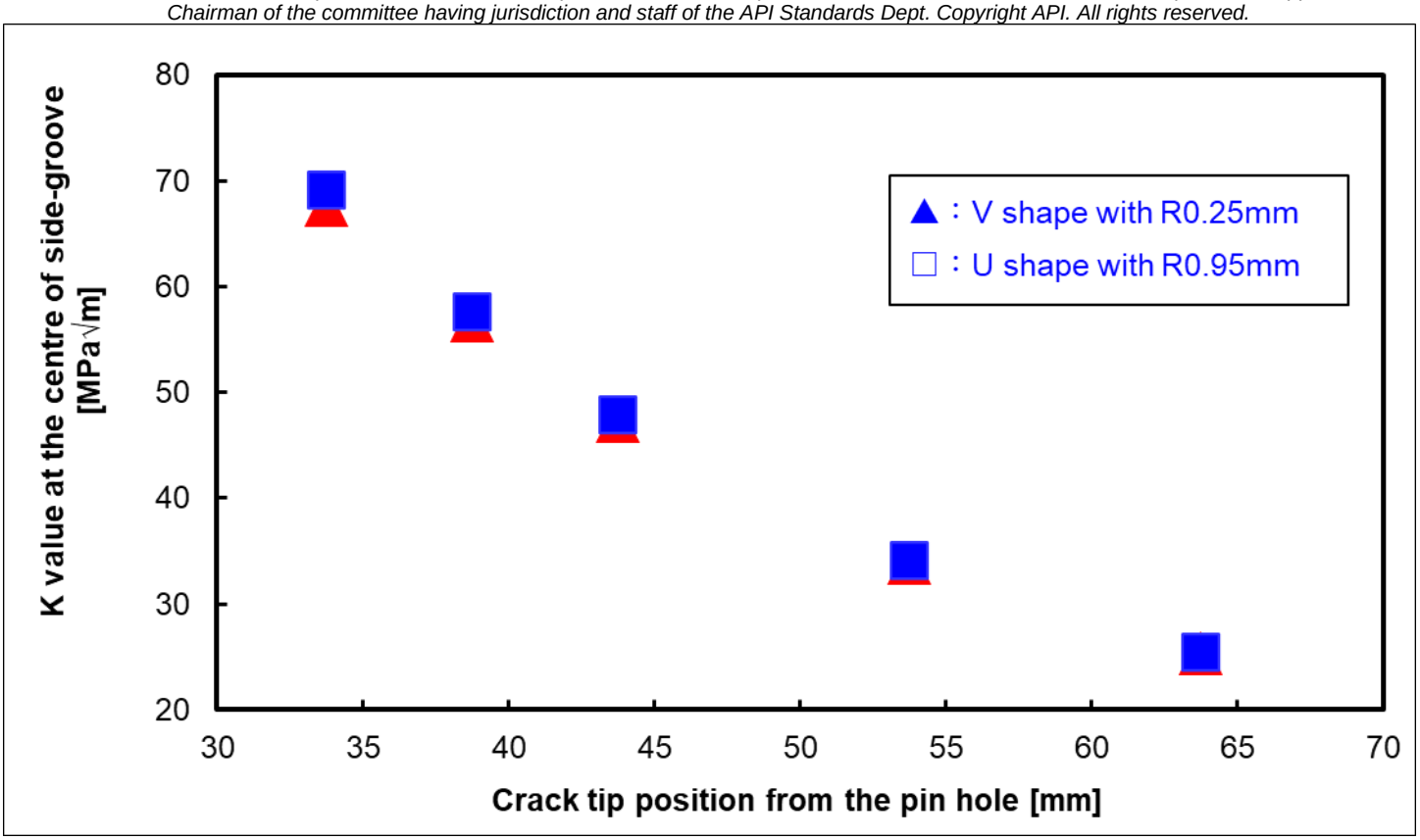


Figure 30—K value at center of side-groove

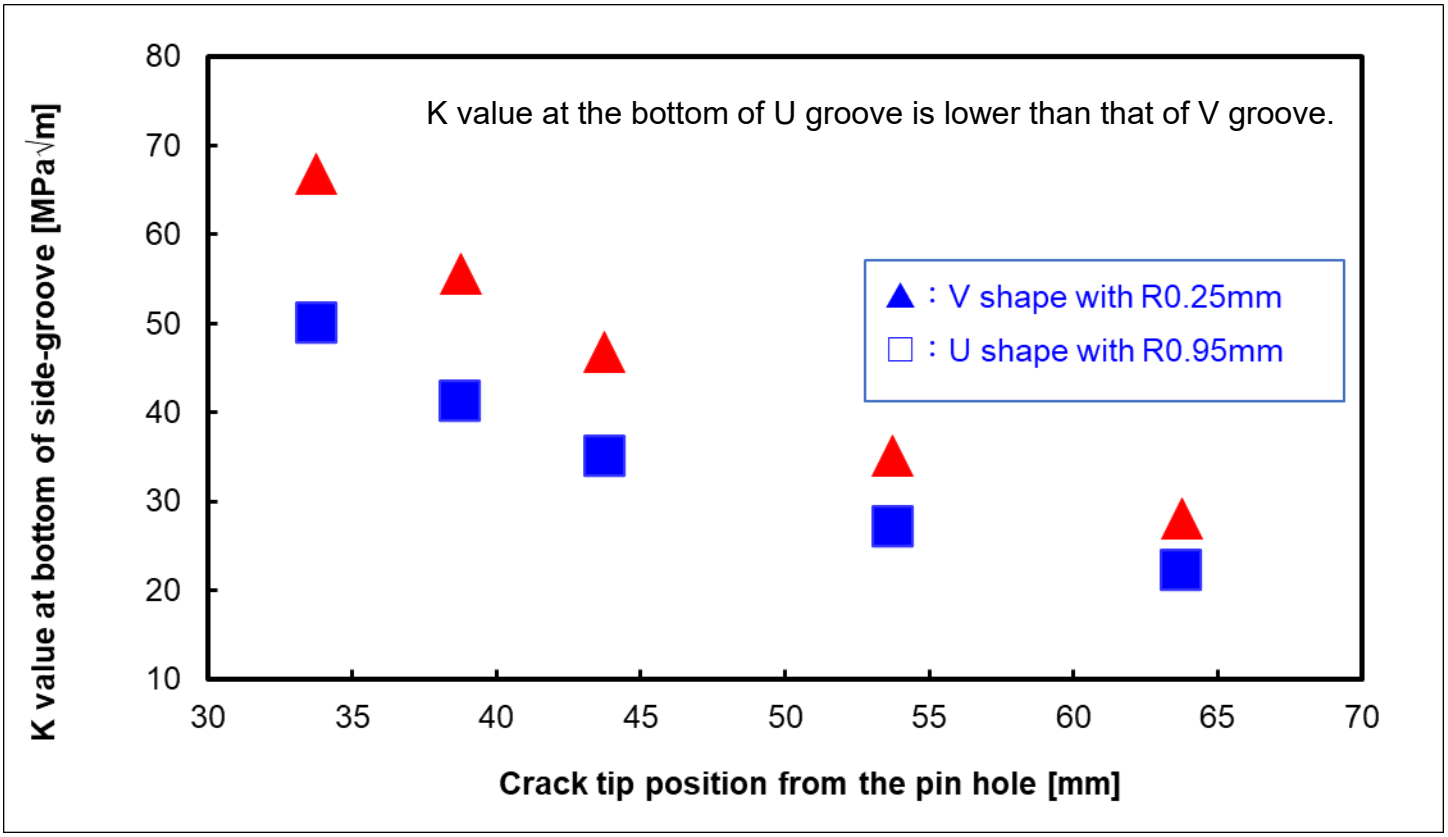


Figure 31—K value at bottom of side-groove

Results of DCB testing

Table 27 shows the K_{Issc} (calculated by formula (1) using the measured final crack length and the final lift-off load at crack arrest). The K_{Issc} values obtained by the U shaped groove is about 15% higher than that using V side-groove. The validation of mechanical aspects of the DCB tests was confirmed as shown by compliance curve evaluation in Figure 32.

The fracture surfaces after DCB testing observed by microscope are shown in Photos 2 and 3. The edge crack could not be observed on the fracture surface of L80. For both the standard V shaped groove and the U shaped groove, non-planar fracture surface, which was evaluated as invalid specified in NACE TM0177 2016, occurred. There is no significant difference in the occurrence of planar surface between V shaped groove and U shaped groove. Non-planar fracture surface was observed using both the standard V shaped groove and the U shaped groove.

From this result, it cannot be determined whether U side-groove configuration is effective or not for reduction of edge crack frequency for L80 material.

Table 27—Results of DCB tests

Side-groove	TP No.	Fatigue Crack Length (mm)	Start Crack Length (mm)	Actual Arm Displacement (mm)	K_{Issc} (ksi√in)	Ave. K_{Issc} (ksi√in)	Hardness from test specimens	Note
V shape with R0.25mm	AT2-1	2.00	33.77	0.823	30.3	31.7	21.0	
	-2	2.00	33.72	0.825	30.3		21.0	Non-planar
	-3	2.00	33.70	0.823	33.2		20.4	
	-4	2.10	33.90	0.825	32.3		20.3	
	-5	2.00	33.79	0.826	31.0		20.2	
	-6	2.00	33.75	0.830	26.5		20.2	Non-planar
U shape with R0.95 mm	AB8-1	2.00	33.74	0.826	38.3	36.3	20.5	Non-planar
	-2	2.00	33.73	0.828	35.6		19.8	Non-planar
	-3	2.00	33.74	0.827	37.3		20.4	
	-4	2.00	33.78	0.822	37.1		20.1	
	-5	2.00	33.75	0.827	34.6		19.9	
	-6	2.00	33.82	0.830	40.0		20.3	Non-planar

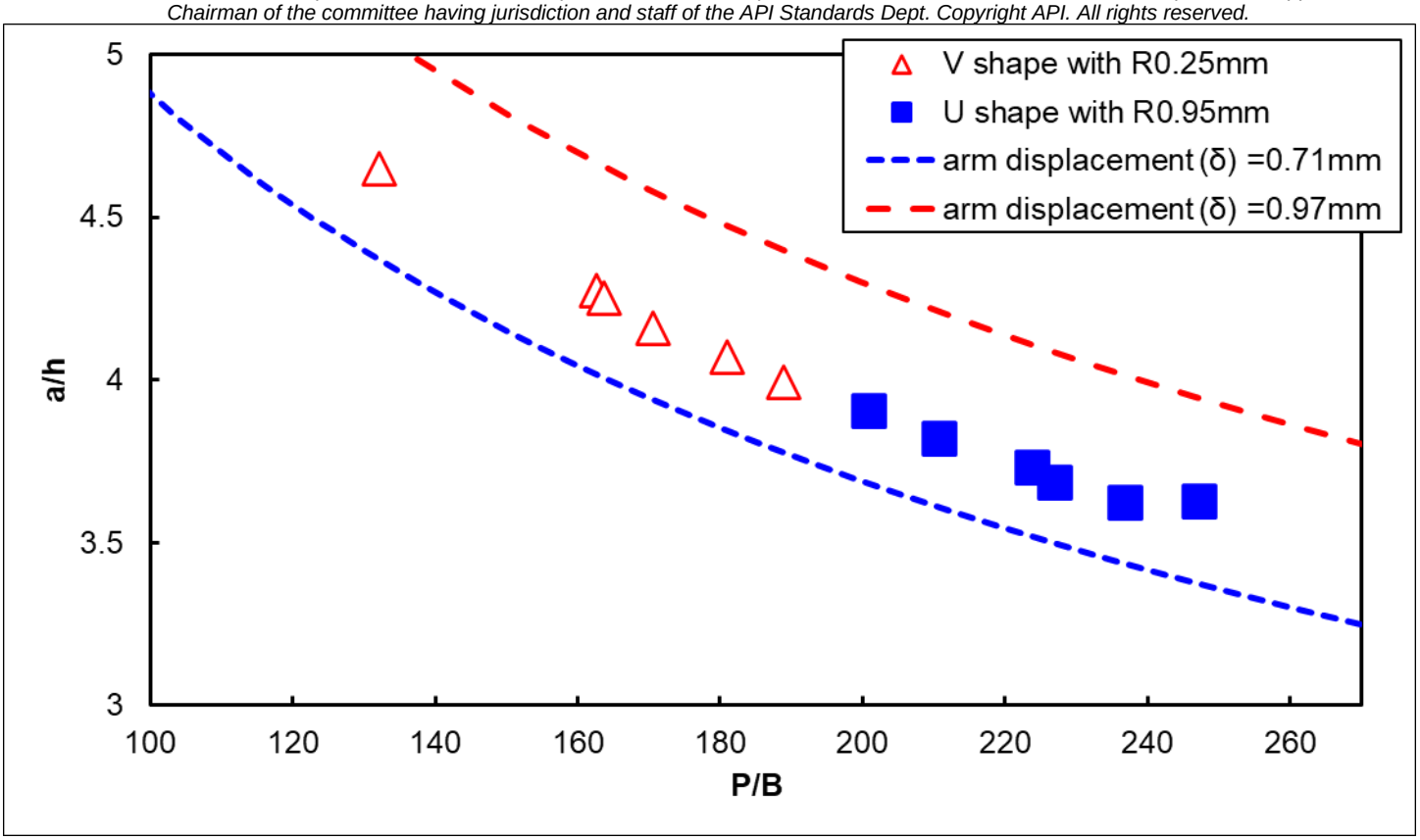


Figure 32. Results of Compliance curve evaluation

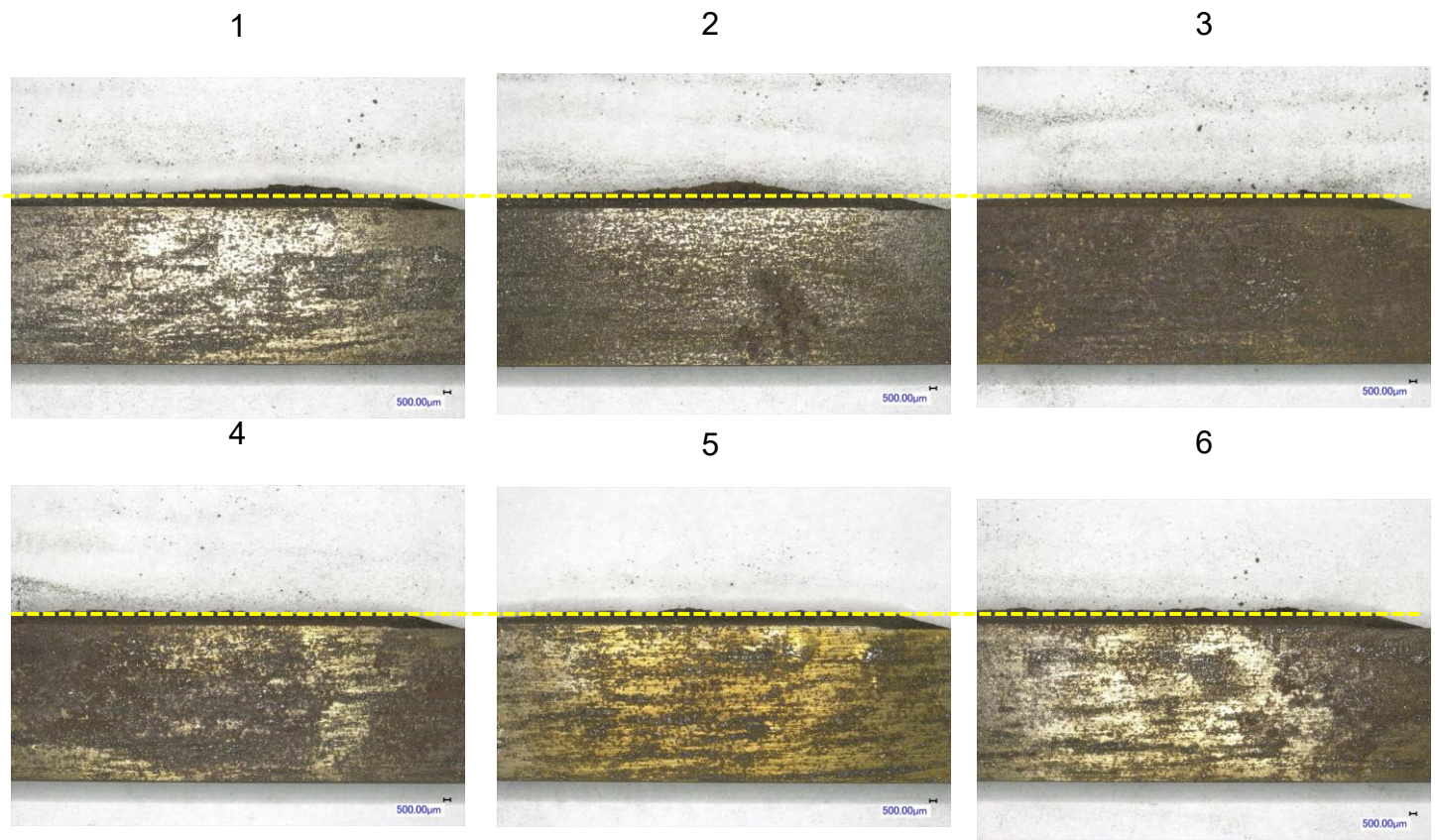


Photo 2. Fracture surface of DCB specimens with the standard V shaped groove (Mark AT2)

U shaped side-groove(AB8)

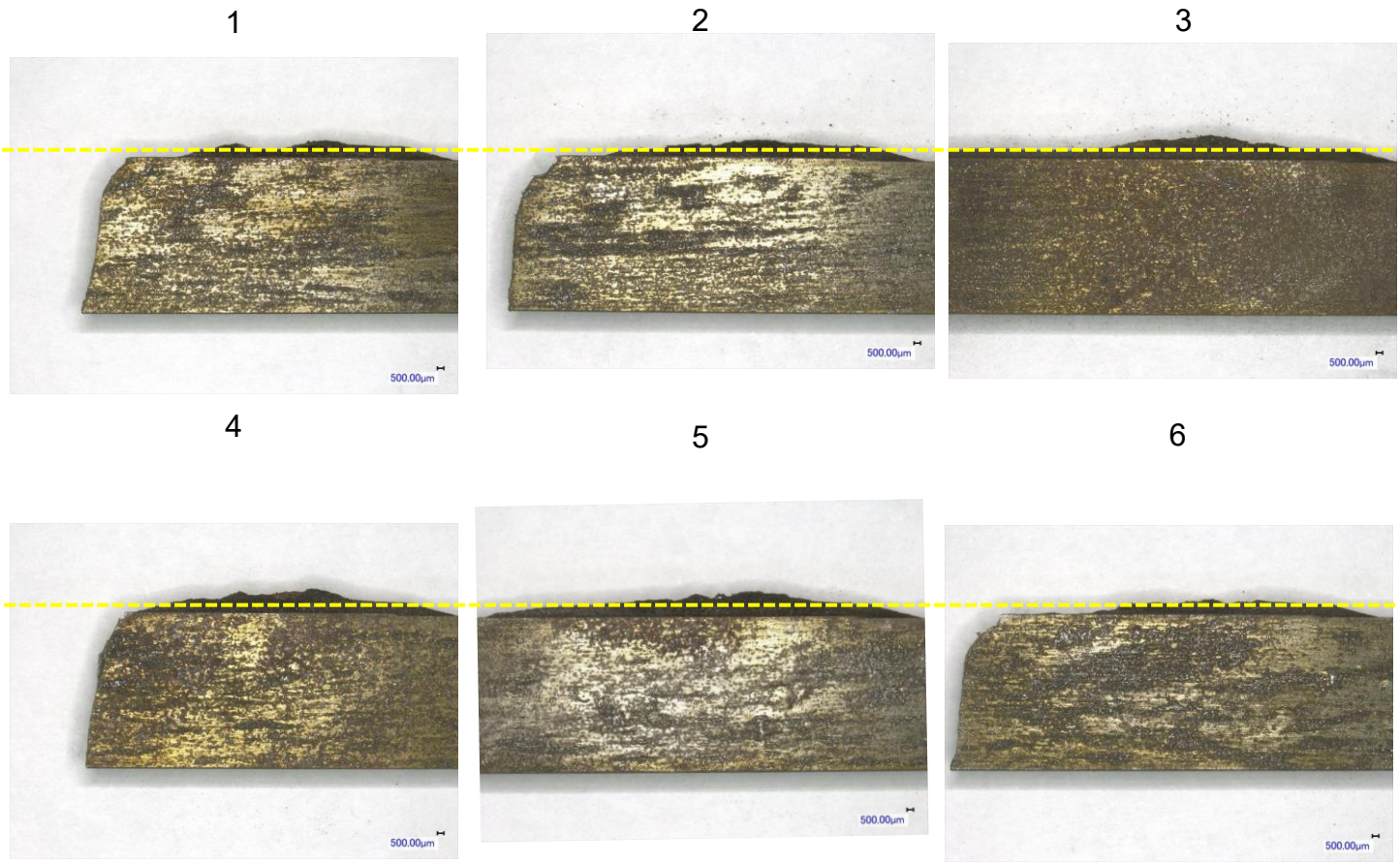


Photo 3. Fracture surface of DCB specimens with the U shaped groove (Mark AB8)

(2) Effect of U side grooves for mild sour conditions for C110 and C125

Since it was reported that the edge crack tends to occur for heavy wall pipe, in addition to C110 material edge crack occurrence was evaluated by DCB tests using another high strength material with specified yield strength of 125 ksi for mild sour service condition.

Testing Materials

Samples were taken from two different pipes with heavy wall thickness and specified minimum yield strength of 110ksi (758MPa, C110) and 125ksi (862MPa, C125) manufactured by Company A as a test material. The pipe size and mechanical properties are shown in Table 28. The chemical composition is shown in Table 29.

Table 28. Pipe size and mechanical properties

Material	Size (mm)	Yield strength		Tensile strength		HRC Mid. wall
		MPa	ksi	MPa	ksi	
C110	OD:250.8 WT:43.73	783	113.36	861	125.2	26.2
C125	OD:355.6 WT:20.32	917	133.0	988	143.4	32.1

Table 29. Chemical compositions (mass%)

Material	C	Mn	P	S	Cr	Mo
C110	0.28	0.44	0.008	0.0014	1.04	0.70
C125	0.27	0.47	0.010	0.0012	0.50	0.71

DCB test procedure

The DCB test according to NACE TM0177 2016 Method D was conducted in test conditions summarized in Table 30. As edge fracture occurred frequently in using high arm displacement, the mild sour condition was selected. One is the NACE solution condition D for C110, and the other condition was discussed in API WI2390 discussed for C125 material in WI2390 at that time.

The test temperature in containers where the DCB specimens were placed was controlled to 24 +/- 1.0°C by isothermal bath with circulating water during test. The DCB specimens were set on the glass holder and electrically isolated. Target arm displacement was set to 0.89mm for the NACE D condition and 0.70mm was set to for C125 condition. All DCB specimens were loaded by wedge insertion with appropriate thickness. The wedge was inserted by vise method.

After exposure, the wedge was removed from the DCB specimen by using a tensile machine at a displacement rate of 0.5mm/min. The lift off load was determined at the abrupt change in the slope of the stress versus strain curve (“Lift-off” curve). After measuring lift-off load, the DCB specimen was chilled with liquid nitrogen and broken with hammer and chisel to measure crack length at crack arrest. Then, the K_{Issc} values were calculated by Equation (1) in the NACE TM0177 2016.

Table 30. DCB test conditions

	C110	125ksi SMYS mild sour service grade
	NACE TM0177-2016 solution D	API WI2390 condition (Being discussed at that time)
Specimen size	Standard size, with U type side-groove	
Wedge material	As quenched material	
Wedge insertion	Vice method	
Test Solution	5.0wt%NaCl+0.4wt%CH_3COONa	
Test gas	0.07 bar H_2S+0.93 bar N_2	0.03 bar H_2S+0.97 bar N_2
Test solution initial pH	between 3.8 and 4.0	3.5
Test duration	408hr	408hr
Target arm displacement	0.89mm	0.70mm
Stirring rate in test solution	100rpm with magnetic stirrer	
Temperature control	24(+/-1.0) ^{o}C	

Results

Results of DCB testing for C110

Table 31 shows the DCB test results for C110 in the NACE D condition. For DCB specimens without pre-crack, Figure 33 shows the relationship between K_{Issc} (calculated by formula (1) using the measured final crack length and the final lift-off load at crack arrest) and HRC hardness of DCB specimens tested in the NACE D condition as mild sour condition. There is no significant difference in the determined K_{Issc} values among the standard V shaped groove and the U shaped groove. While, Figure 34 for DCB specimens with pre-crack, K_{Issc} values using the U shaped groove with R0.95mm is slightly higher (about 8%) than those by using V side-groove.

As shown in Figure 35 for the specimens without pre-crack and Figure 36 for the specimens with pre-crack, the occurrence of edge crack was suppressed by using the U shaped groove with R0.95mm compared with the standard V shaped groove with R0.25mm. Example of edge cracks after tests for C110 is shown in Photo 4.

Figures 37 and 38 shows comparison of the difference in crack length between at bottom of the groove and center of the width. For the U shaped groove, crack propagated through the width uniformly compared with that of the standard V shaped groove. Crack at edge (outer) surface propagated easier than center of thickness using V shaped groove.

Table 31. Results for C110 in the NACE D condition

Notch type	Side-groove	TP No.	Fatigue Crack Length (mm)	Start Crack Length (mm)	Actual Arm Displacement (mm)	K_{Issc} (ksi√inch)		Hardness from test specimens	remarks
						Each	Avg.		
(A) Chevron notch	V shape with R0.25mm	110AV-1	0.00	31.82	0.878	50.5	52.0	26.1	
		110AV-2	0.00	31.81	0.885	52.0		27.0	e
		110AV-3	0.00	31.73	0.880	56.2		25.9	
		110AV-4	0.00	31.76	0.885	50.3		26.4	
		110AV-5	0.00	31.76	0.882	50.6		25.9	
		110AV-6	0.00	31.76	0.883	52.3		25.7	
	U shape with R0.95mm	110AU-1	0.00	31.76	0.880	55.2	53.0	26.5	
		110AU-2	0.00	31.75	0.885	53.4		26.3	e
		110AU-3	0.00	31.78	0.884	53.7		26.5	
		110AU-4	0.00	31.79	0.885	50.8		26.7	
		110AU-5	0.00	31.69	0.885	53.9		26.5	
		110AU-6	0.00	31.70	0.883	51.1		26.3	
			(mm)	(mm)	(mm)	Each	Avg.		
(B) Chevron notch + pre-crack	V shape with R0.25mm	110BV-1	2.00	33.84	0.879	48.4	49.0	26.8	
		110BV-2	2.00	33.82	0.875	48.9		26.5	e
		110BV-3	2.00	33.81	0.878	50.0		26.9	
		110BV-4	2.00	33.80	0.877	49.3		26.9	
		110BV-5	2.00	33.80	0.875	50.0		26.6	
		110BV-6	2.00	33.83	0.871	47.2		26.4	e
	U shape with	110BU-1	2.00	33.76	0.879	53.7	53.2	26.7	
		110BU-2	2.00	33.85	0.882	54.0		26.9	

	R0.95mm	110BU-3	2.00	33.74	0.881	53.1		26.5	
		110BU-4	2.00	33.66	0.883	53.6		26.6	
		110BU-5	2.00	33.86	0.881	52.1		26.5	
		110BU-6	2.00	33.83	0.877	52.7		26.7	

e: edge crack

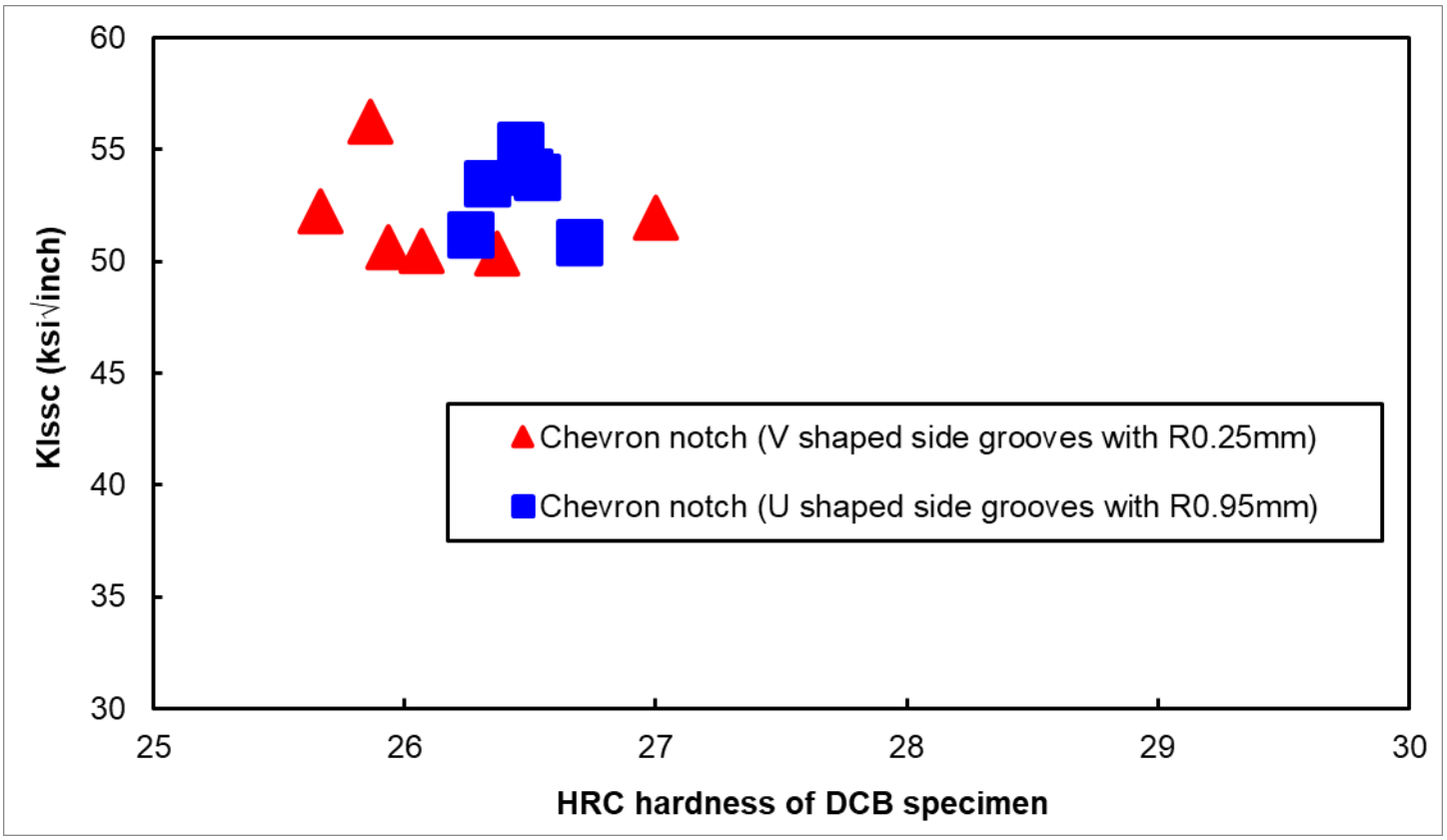


Figure 33. Comparison of K_{Issc} for DCB specimens without pre-crack for C110 material

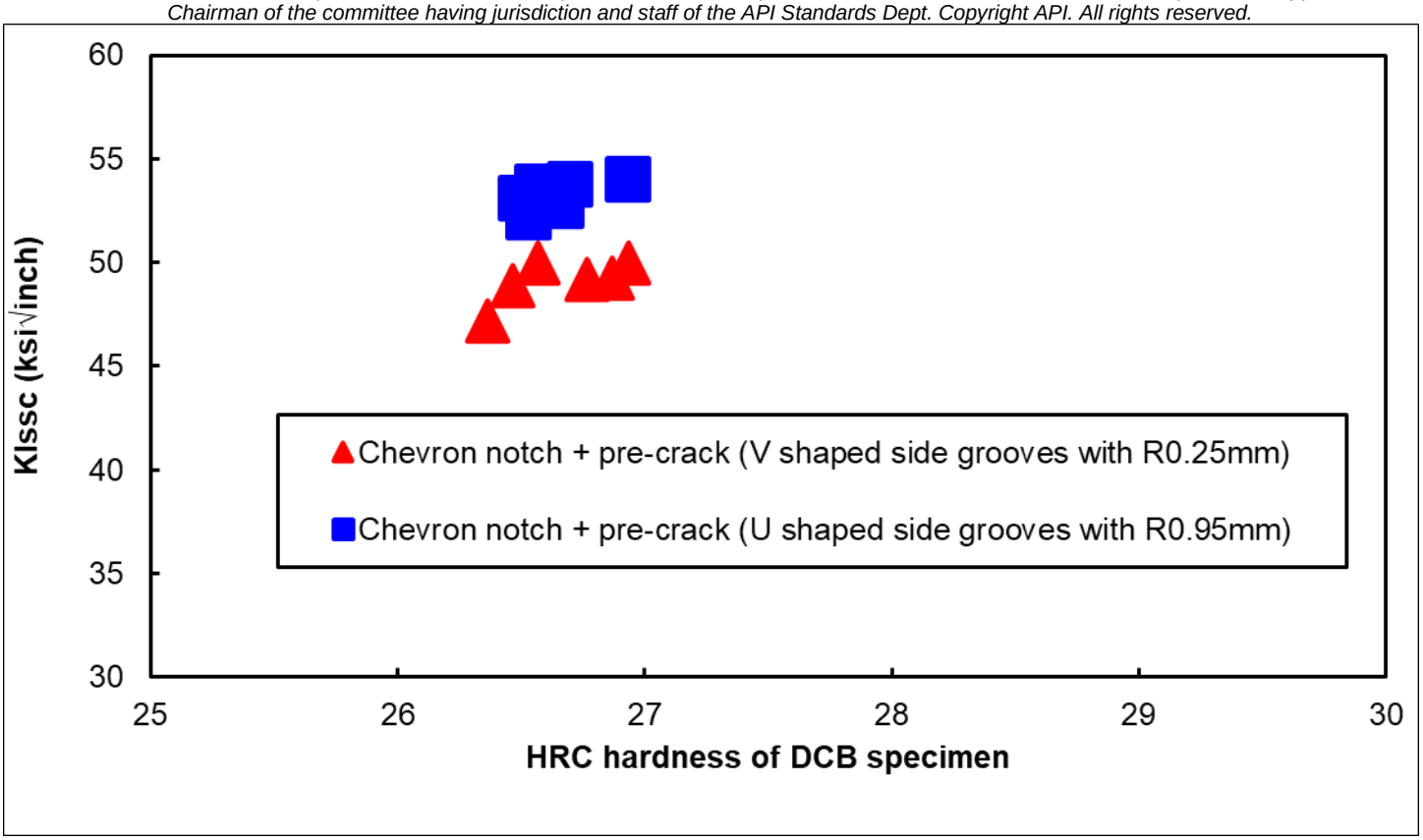


Figure 34. Comparison of K_{Issc} for DCB specimens with pre-crack for C110 material

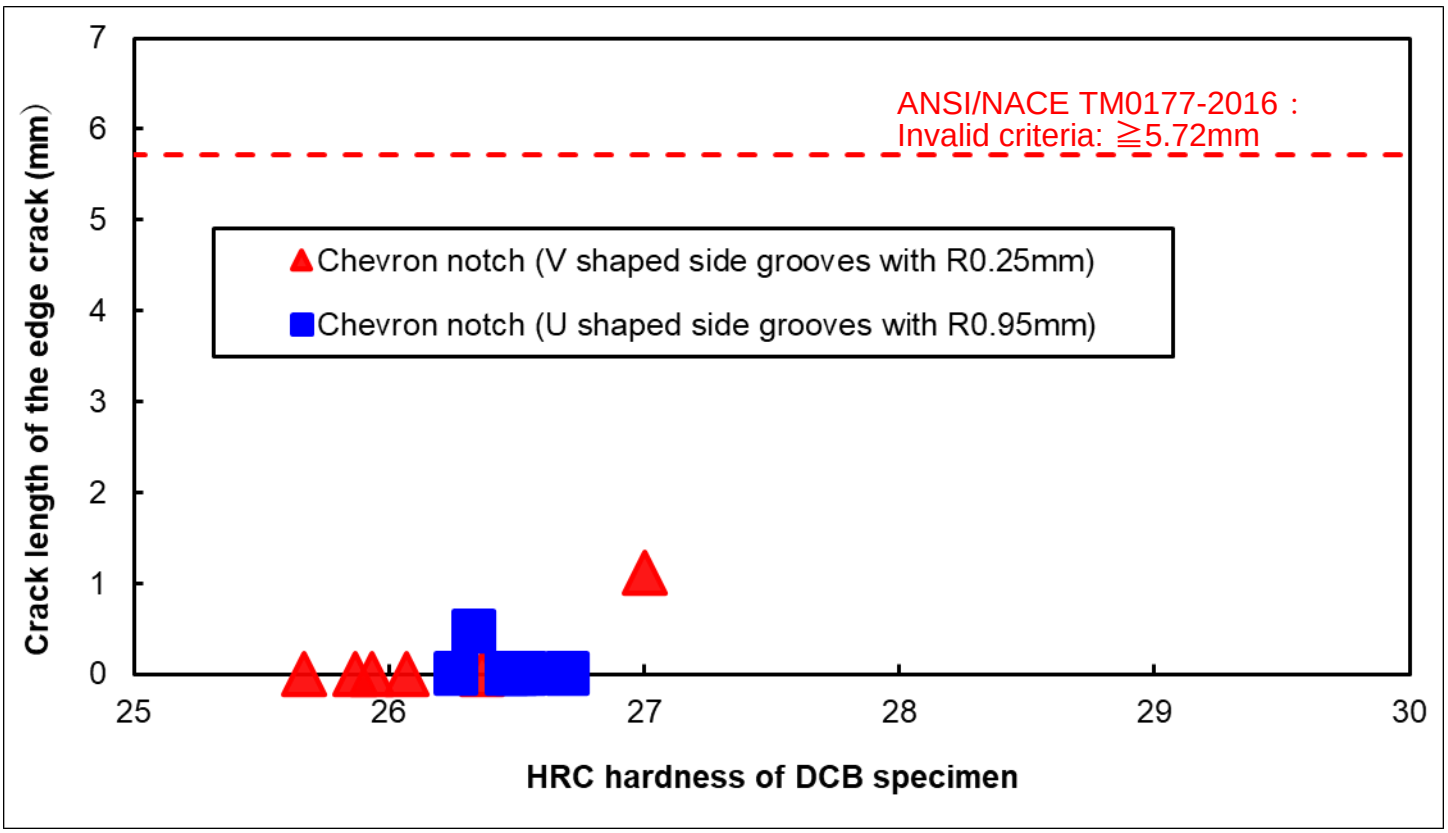


Figure 35. Comparison of the occurrence of edge crack for DCB specimens without pre-crack for C110 material

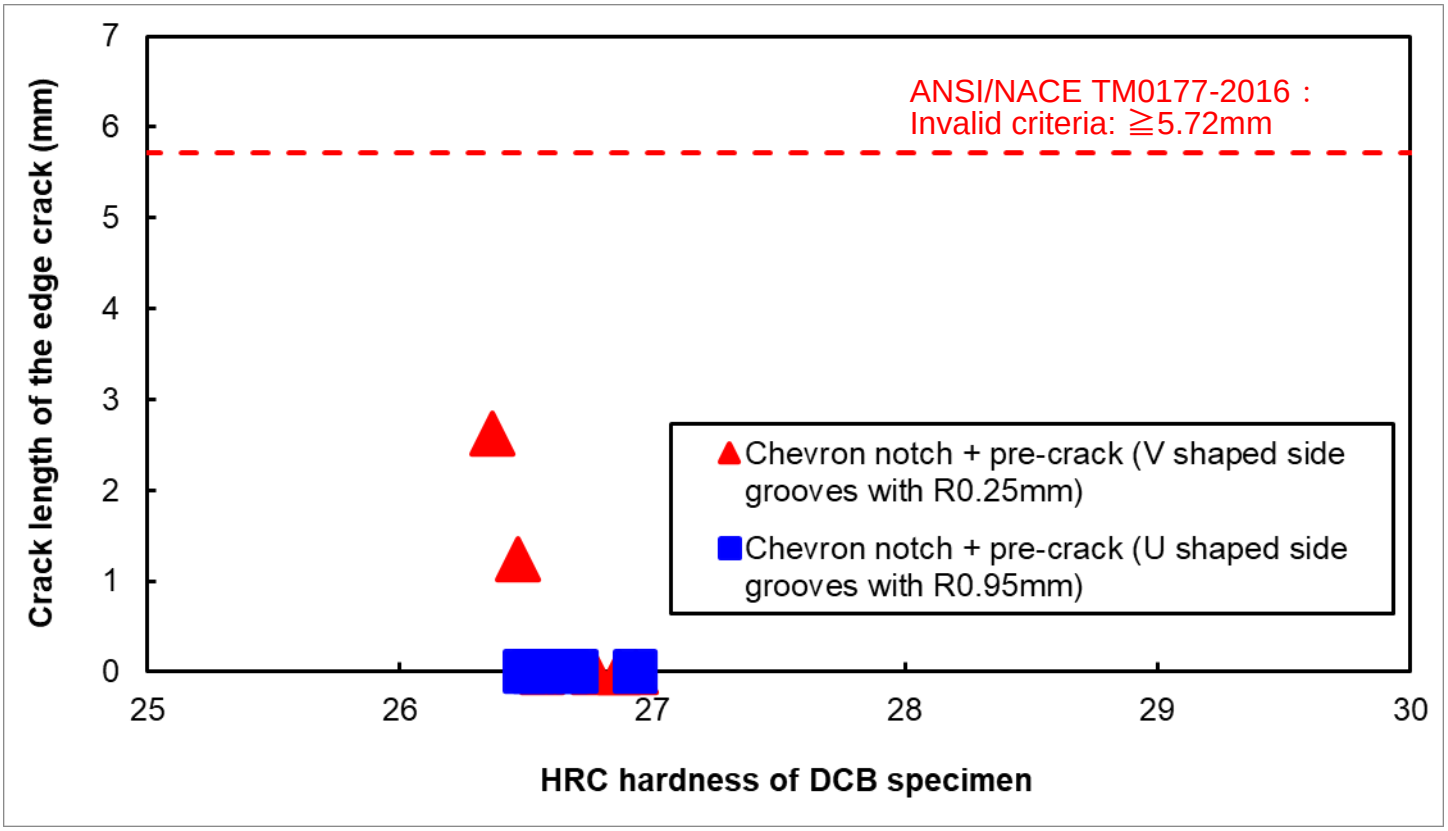
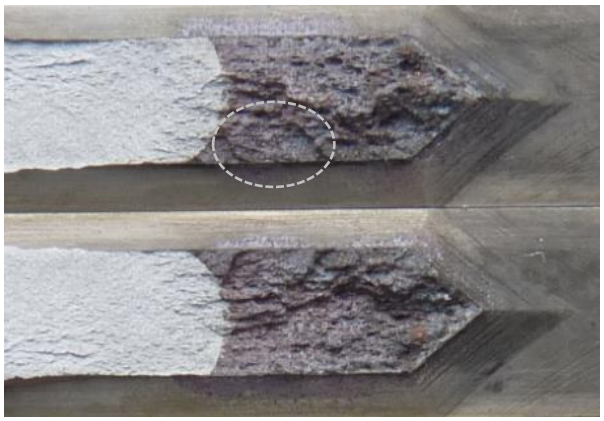


Figure 36. Comparison of the occurrence of edge crack for DCB specimens with pre-crack for C110 material



C110
(Mark:110AV-2, V shape with R0.25mm)

C110
(Mark:110BV-2, V shape with R0.25mm)

C110
(Mark:110AU-2, U shape with R0.95mm)

C110
(Mark:110BV-6, V shape with R0.25mm)

Photo 4 Example of edge cracks after tests for C110 (edge crack is surrounded by white dotted line)

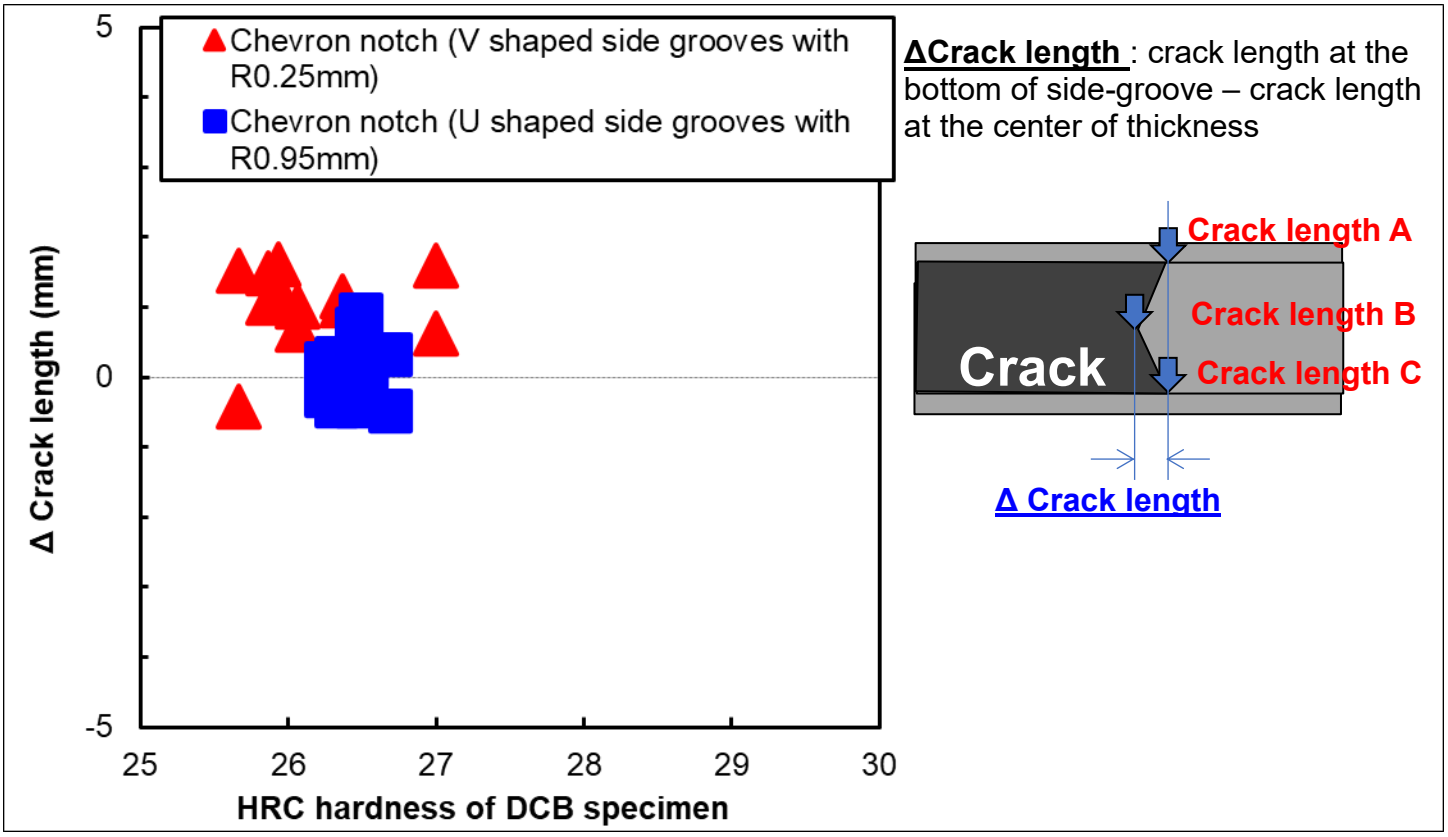


Figure 37. Difference of crack length between at bottom of the groove and at center of the width

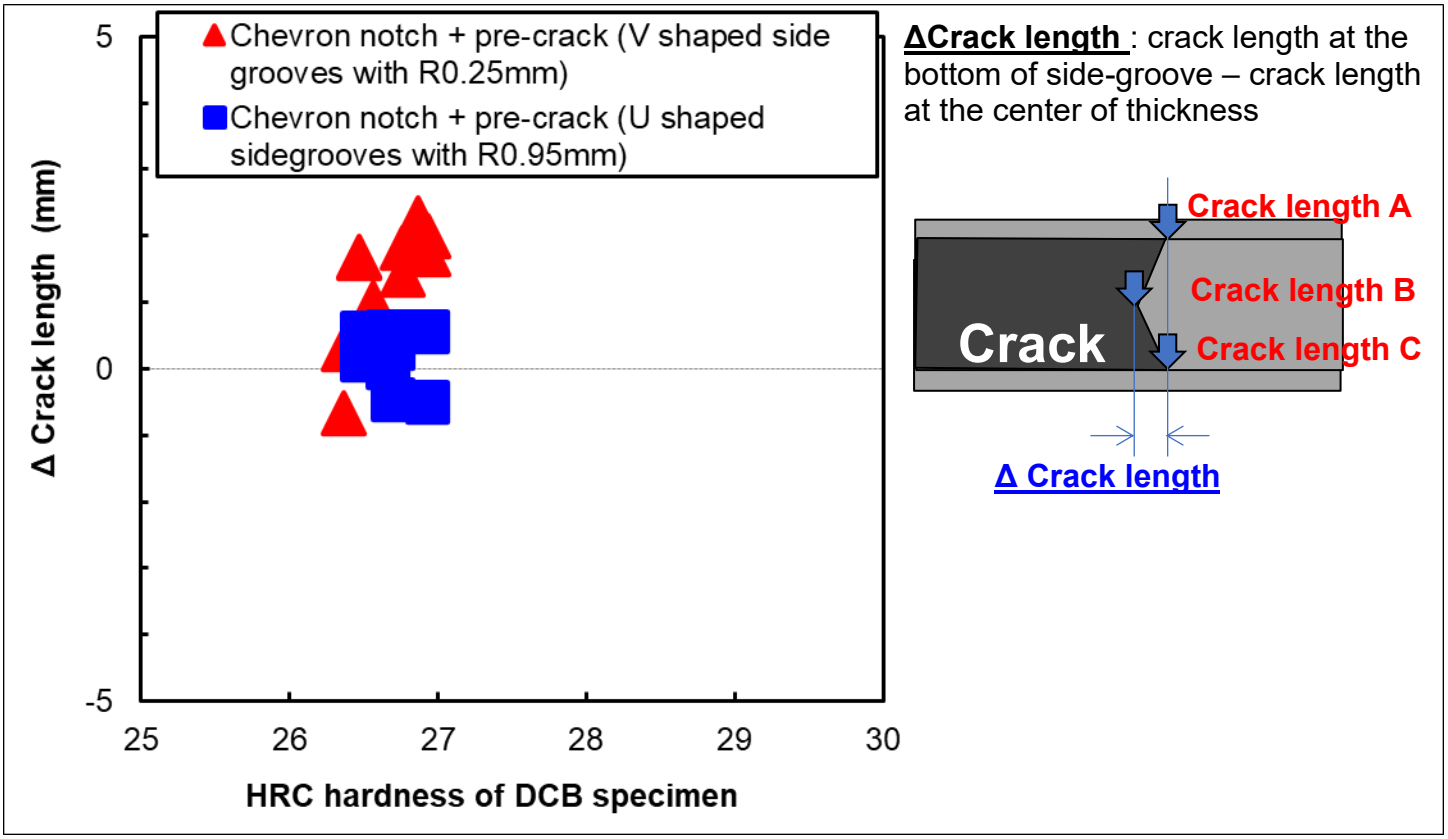


Figure 38. Difference of crack length between at bottom of the groove and at center of the width

Results of DCB testing for C125 material

Table 32 shows the DCB test results for C125 in 5.0wt%NaCl+0.4wt%CH_3COONa, 0.03 bar H_2S balanced with N_2 environment. For DCB specimens without pre-crack, Figure 39 shows the relationship between K_{Issc} and HRC hardness of DCB specimens. There is no significant difference in the K_{Issc} values among the standard V shaped groove and the U shaped groove. As shown in Figure 40 for DCB specimens with pre-crack, there is also no significant difference in the K_{Issc} values among the standard V shaped groove and the U shaped groove.

As shown in Figure 41 for the specimens without pre-crack and Figure 42 for the specimens with pre-crack, the occurrence of edge crack was suppressed by using the U shaped groove with R0.95mm compared with the standard V shaped groove with R0.25mm. Example of edge cracks after tests is shown in Photo 5.

Figures 43 and 44 show comparison of the difference in crack length between at bottom of the groove and center of the width. For the U shaped groove, crack propagated through the width uniformly compared with that of the standard V shaped groove. Crack at edge (outer) surface propagated easier than center of thickness using V groove.

Table 32. Results of DCB tests for C125 material

Notch type	Side-groove	TP No.	Fatigue Crack Length	Start Crack Length	Actual Arm Displacement	K_{Issc} ksi√inch		Hardness from test specimens	remarks
			(mm)	(mm)	(mm)	Each	Avg.		
(A) Chevron notch	V shape with R0.25mm	125AV-1	0.00	31.81	0.721	29.9	23.8	31.4	e
		125AV-2	0.00	31.78	0.739	23.9		31.4	
		125AV-3	0.00	31.76	0.708	20.4		31.8	e
		125AV-4	0.00	31.75	0.724	22.8		31.6	e
		125AV-5	0.00	31.76	0.734	23.3		31.9	
		125AV-6	0.00	31.74	0.710	22.4		32.0	
	U shape with R0.95mm	125AU-1	0.00	31.63	0.717	22.4	23.7	31.3	e
		125AU-2	0.00	31.63	0.721	27.3		31.7	e
		125AU-3	0.00	31.65	0.714	21.9		31.6	
		125AU-4	0.00	31.63	0.716	28.0		32.1	
		125AU-5	0.00	31.65	0.715	20.7		31.5	
		125AU-6	0.00	31.65	0.711	22.1		32.2	e
(B)	V shape with	125BV-1	2.00	33.71	0.714	21.3	22.2	31.5	

Chevron notch + pre-crack	R0.25mm	125BV-2	2.00	33.78	0.708	23.1		31.6	
		125BV-3	2.00	33.81	0.712	22.2		31.3	e
		125BV-4	2.00	34.03	0.714	22.3		32.0	
		125BV-5	2.00	34.06	0.715	21.3		30.9	
		125BV-6	2.00	33.85	0.716	23.1		31.3	
	U shape with R0.95mm	125BU-1	2.00	33.81	0.721	21.9	23.0	31.6	
		125BU-2	2.00	33.68	0.711	22.2		31.9	
		125BU-3	2.00	33.76	0.713	24.0		31.0	
		125BU-4	2.00	33.67	0.717	23.5		31.8	
		125BU-5	2.00	33.66	0.720	21.9		31.9	
		125BU-6	2.00	33.69	0.724	24.3		31.7	

e: edge crack

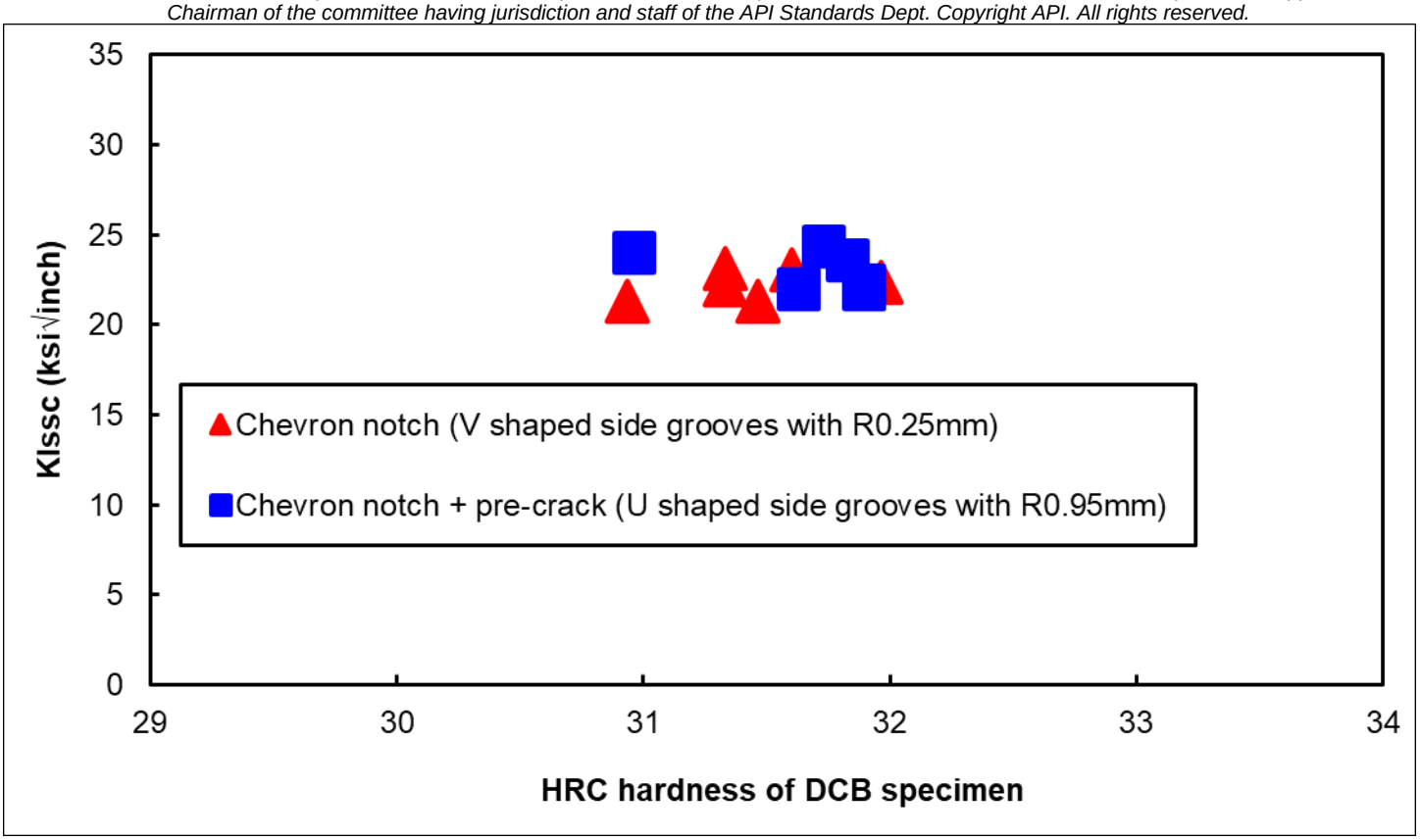


Figure 39. Comparison of K_{Issc} for DCB specimens without pre-crack for C125 material

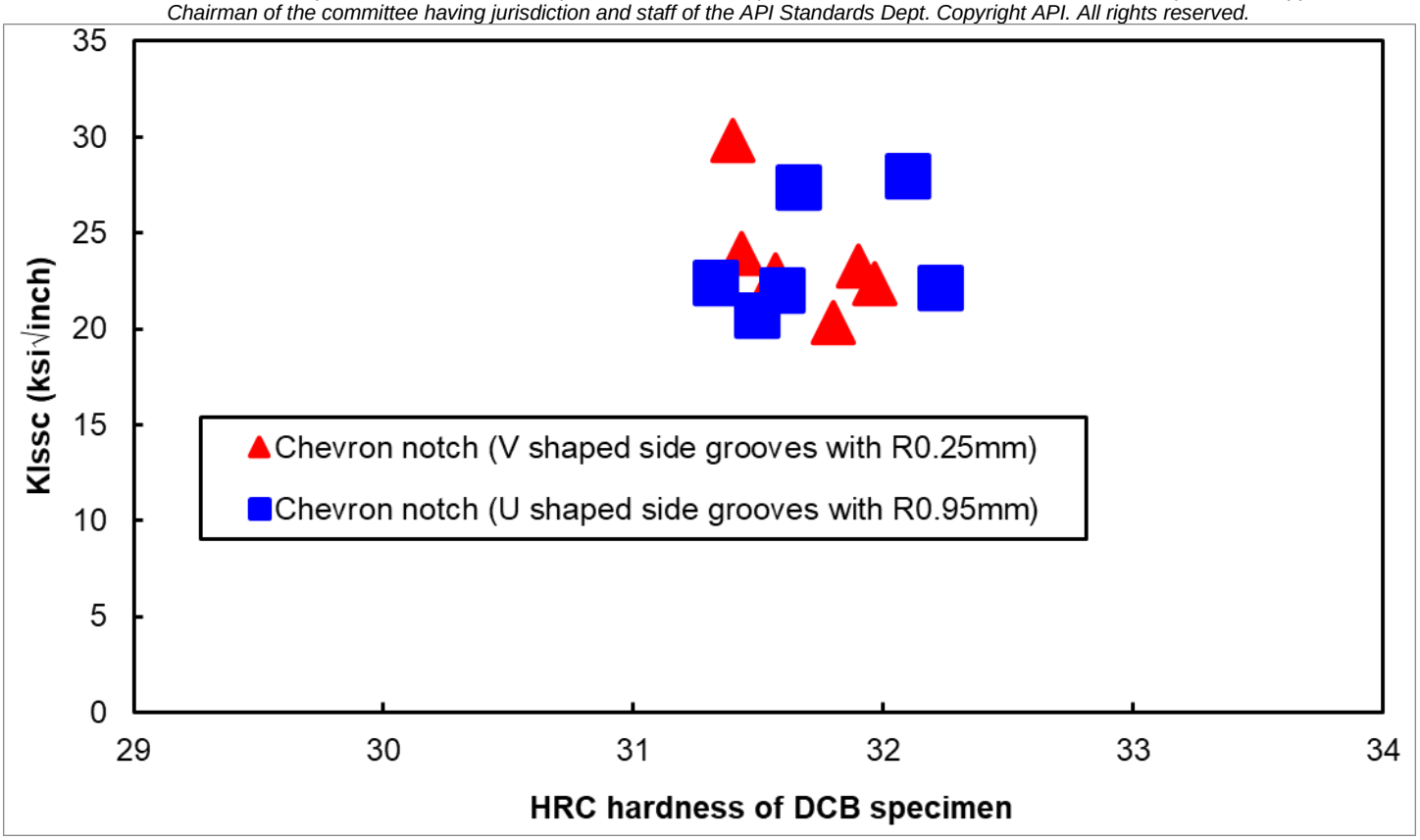


Figure 40. Comparison of K_{Issc} for DCB specimens with pre-crack for C125 material

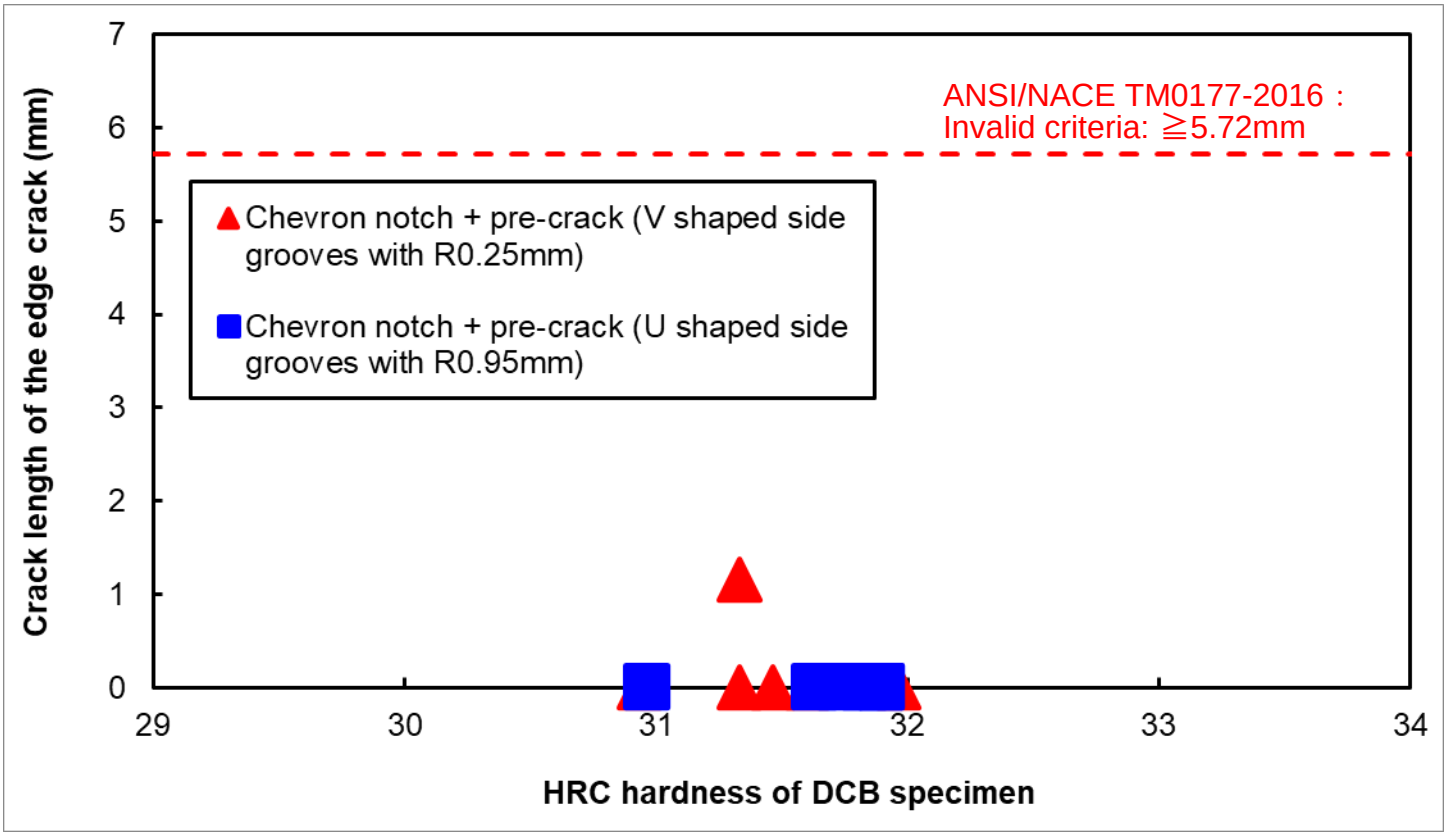


Figure 41. Comparison of the occurrence of edge crack for DCB specimens without pre-crack for C125

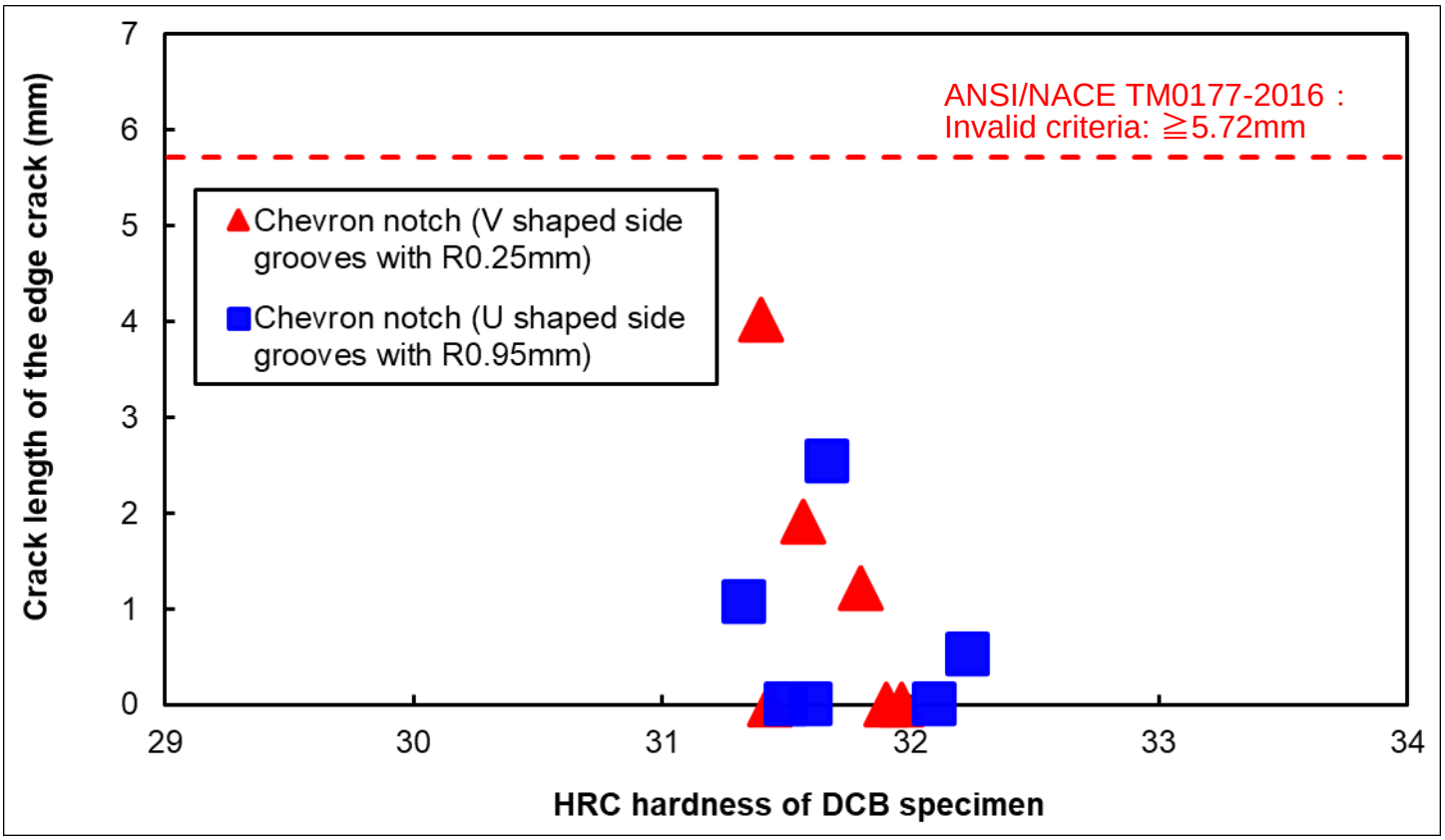
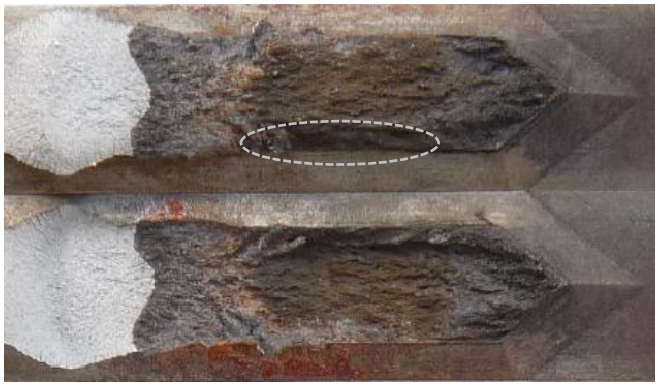
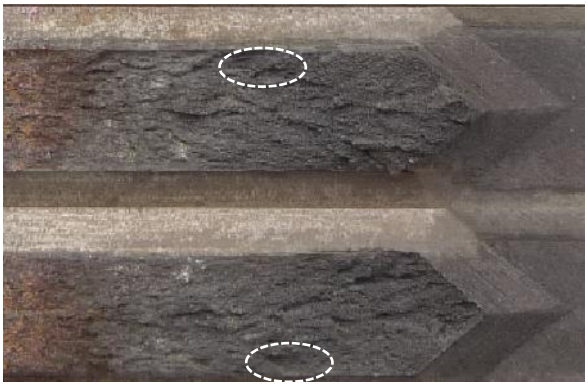


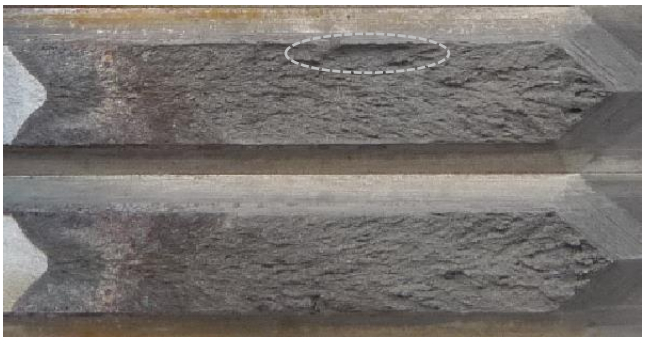
Figure 42. Comparison of the occurrence of edge crack for DCB specimens with pre-crack for C125



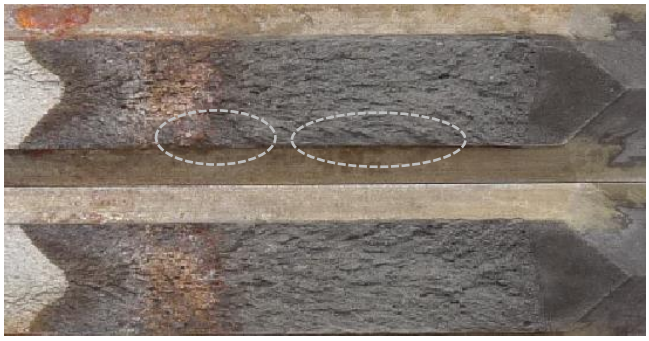
C125 (Mark:125AV-1, V shape with R0.25mm)



C125 (Mark:125AV-4, V shape with R0.25mm)



C125 (Mark:125AV-3, V shape with R0.25mm)



C125 (Mark:125BV-3, V shape with R0.25mm)

C125 (Mark: 125AU-1, U shape with R0.95mm)

C125 (Mark:125AU-2, U shape with R0.95mm)

C125 (Mark:125AU-6, U shape with R0.95mm)

Photo 5 Example of edge cracks after tests for C125 (edge crack is surrounded by white dotted line)

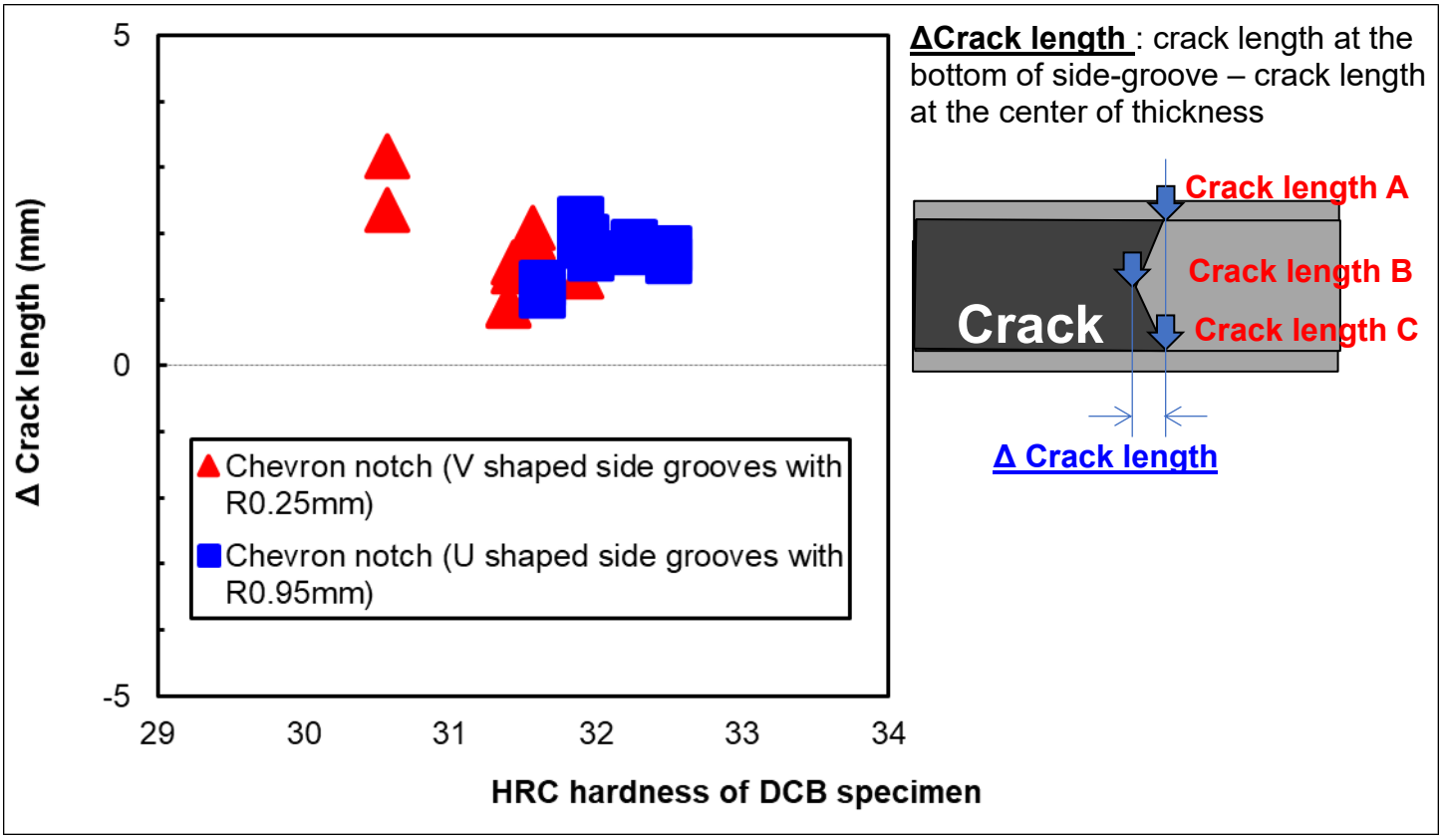


Figure 43. Difference of crack length between at bottom of the groove and at center of the width

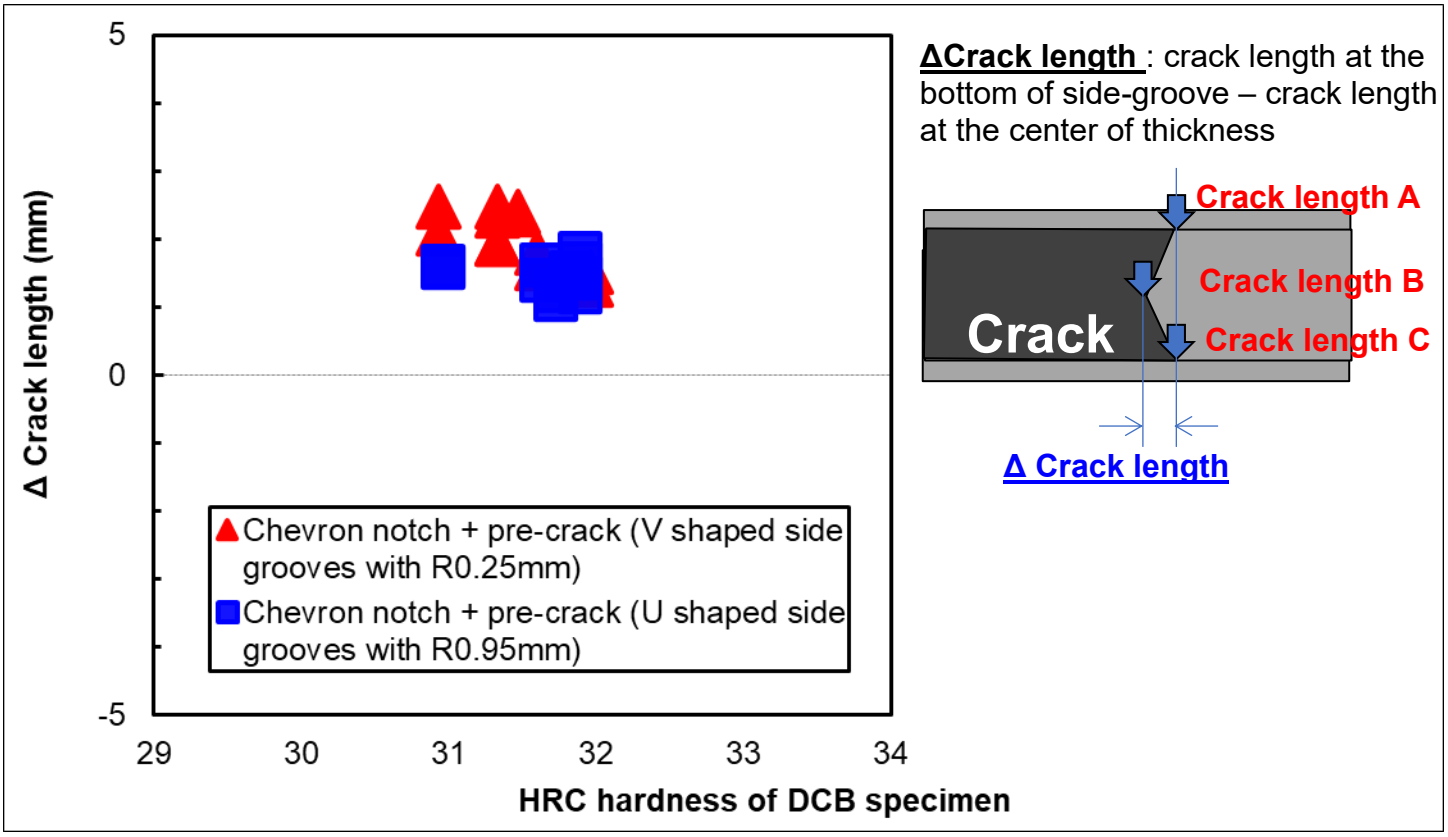


Figure 44. Difference of crack length between at bottom of the groove and at center of the width.

(3) Comparison of effect of U side groove between Company A and Company B

In API WI2413 (DCB side groove study), the results between Company A and Company B were compared in terms of not only for reducing edge cracks but also for non-planar fracture surface.

DCB Test Summary in API WI2413 (DCB side groove study)

Table 33 shows the results of DCB testing in Company A for C110（1 bar H_2S-saturated NACE Sol. A, NACE Sol. D condition）& C125 (NACE Sol. B, 0.03 bar H_2S balanced with N_2 environment). For both conditions, the occurrence of edge crack is decreasing by using the U shaped groove with R0.65mm and with R0.95mm, and there is no problem with non-planar fracture surface. While, as shown in Table 34 for the results of DCB testing in Company B using Company B's U shaped groove with R0.65mm and the standard V groove with R0.25mm. For condition of C110 in 1 bar H_2S-saturated NACE Sol. A, although the cause of occurrence of the short crack is not clear (probably it could be solved by applying pre-crack), there is no problem for the U groove with R0.65mm in terms of both the occurrence of edge crack and non-planar surface. For C125 in NACE Sol. B, 0.03 bar H_2S balanced with N_2 environment), there was a high probability to occur non-planar fracture surface.

As a common result obtained from this comparison, the U side groove with R0.65mm was effective for C110 in 1 bar H_2S-saturated NACE Sol. A.

Table 33. Results of Company A

Company A						
Grade	API C110				C125	
Pipe size	OD311.15mmxWT28.58mm		OD305mmxWT36.6mm OD250.8mmxWT43.73mm		OD355.6mmxWT20.32mm	
Gas	1 bar H_2S		0.07 bar H_2S balanced with N_2		0.03 bar H_2S Balanced with N_2	
Solution	NACE A		NACE D		NACE B	
Test specimen	Chevron notch with pre-crack 2mm		Chevron notch with pre-crack 2mm		Chevron notch with pre-crack2mm	
Arm displacement	0.51mm		0.89mm		0.71mm	
Invalid	edge crack	non planar	edge crack	non planar	edge crack	non planar
R0.95 (U)	OK	OK	OK	OK	OK	OK
R0.65 (U)	OK	OK	-	-	-	-
R0.25 (V)	**Fail**	OK	**Fail**	OK	**Fail**	OK
Remarks (API)	2019/06		2016/6 2018/6		2018/6	

Table 34. Results of Company B

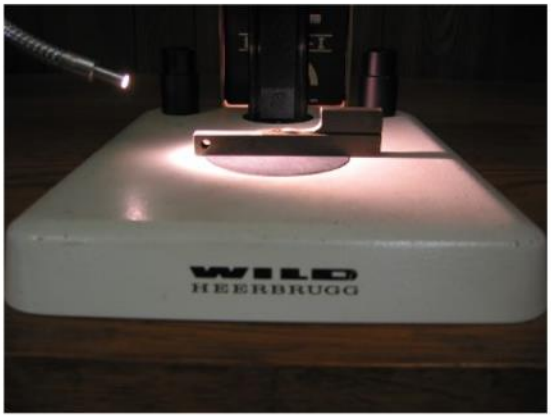
Company B										
Grade	C110			C125						
Pipe size	OD244.48mmxWT13.84mm			OD250.83mm x WT16.79mm OD250.83mm x WT15.88mm						
Gas	1 bar H_2S			0.03 bar H_2S balanced with N_2						
Solution	NACE A			NACE B						
Test specimen	Chevron notch			Chevron notch with pre-crack 2mm						
Arm displacement	0.51mm			0.4mm			0.51mm		0.71mm	
Invalid	edge crack	non planar	short crack	edge crack	non planar	short crack	edge crack	non planar	edge crack	non planar
R0.95 (U)	OK	OK	**Fail**	OK	**Fail**	OK	-	-	-	-
R0.65 (U)	OK	OK	**Fail**	OK	OK	**Fail**	OK	**Fail**	OK	**Fail**
R0.25 (V)	OK	OK	OK	OK	OK	OK	-	-	-	-
Remarks (API)	January, 2020			June, 2018 June, 2019						

(4) Fracture surface evaluation for inspection of edge crack in Sec. 5.2.1

Proposed method to reveal edge crack

Company A received the recommendation from one of API WI2413 (DCB side groove study) members to use the low-angle illumination with fiber-optics light in order to reveal the edge crack

Setup

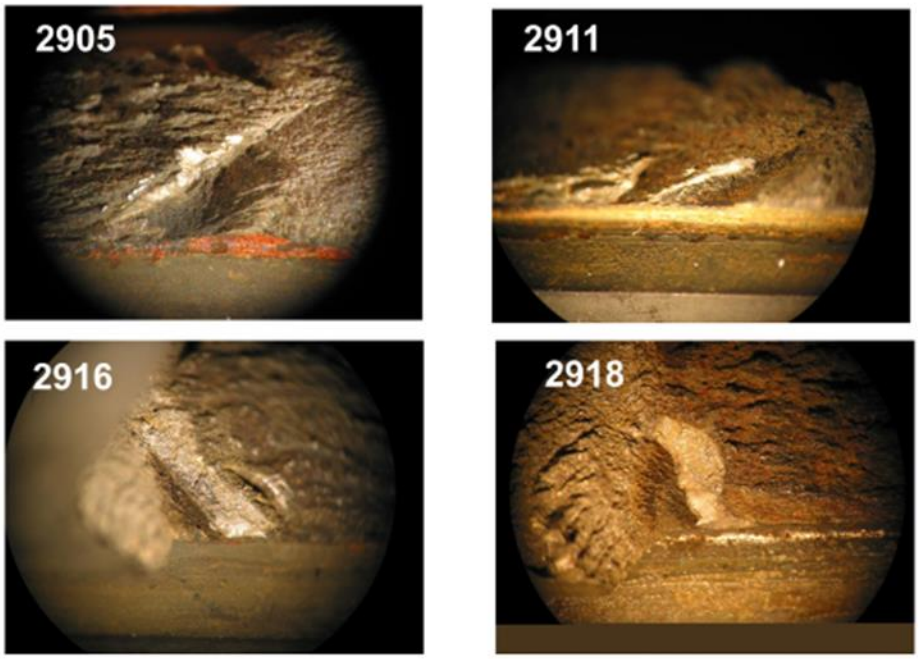


Example of edge crack revealed by low-angle illumination

Low-angle Illumination is from the left (upper) and from the right (lower).

Suggestion from one of WI2413 members
"But not every edge crack causes 'trouble' by giving false, high K_{ISSC} values. Only the ones where the broken ligament between the top and bottom arms ['Leaf Spring'] shows a significant amount of shiny, rubbed, sheared, or cleavage surface when examined for reflection under direct, bright light, should the transverse length of the leaf spring(s) be measured to see if the specimen is invalid."

Example of significant edge crack presented by one of API WI2413 (DCB side groove study) members



Example of insignificant edge crack presented by one of API WI2413 (DCB side groove study) members

Example of insignificant edge crack presented by one of API WI2413 (DCB side groove study) members

- Company A ran the low angle illumination method to reveal the edge crack using the test

specimens in order to verify the effect of U side groove

Company A's inspection results

Definition of edge-crack according to 11.6.1 in NACE TM0177 2016

1. The combined width of any edge crack(s) at the crack front on the fracture surface shall not exceed 25% of the web thickness Bn for a valid test.

2. Edge cracks lying away from the crack front (that formed earlier in the test) shall be given one-fourth the weight of those at the crack front. Thus, a DCB specimen whose earlier-formed edge cracks have a combined width exceeding 100% of the web thickness shall be invalid.

3. For DCB test specimens with both earlier-formed edge cracks and edge cracks at the crack front, the sum of the combined widths of the earlier-formed edge cracks divided by four, plus the widths of those at the crack front, shall not exceed 25% of the web thickness, Bn, for the test to be considered valid

Review of NACE method D test data (machining: Third party→DCB testing: Company A→Fracture surface evaluation: Company A)

ID	Configuration of side groove	K1ssc		Hardness from DCB specimens	Total width of edge cracks (mm)	Validation in accordance with 11.6.1 e)
		Each	Avg.			
		ksi√inch				
292	V shape with R0.25mm	28.4	29.3	26.7	**13.23**	Invalid (sub clause 3)
293		29.8		26.6	4.00	valid
294		29.2		26.1	2.03	valid
295		29.9		26.7	3.13	Invalid (sub clause 3)
296		28.1		25.9	2.23	valid
332	U shape with R0.65mm	30.2	29.9	26.7	1.02	valid
333		31.5		26.6	1.86	valid
334		29.7		26.7	1.96	valid
335		29.3		26.7	5.40	valid
336		28.9		26.7	3.84	Invalid (sub clause 3)
347	U shape with R0.95mm	29.9	28.0	26.7	1.43	valid
348*		31.2		26.1	0.00	valid
349		26.9		26.9	3.62	valid
350		27.1		26.7	4.77	valid
351		28.1		26.7	0.00	valid

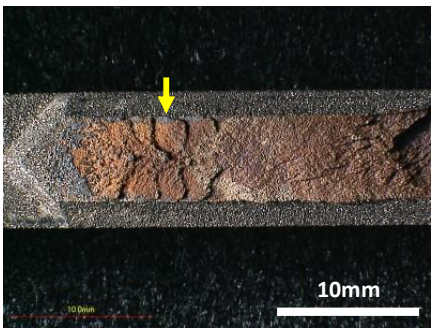
*Invalid due to short crack in accordance with 11.6.1.a)

Setup in Company A

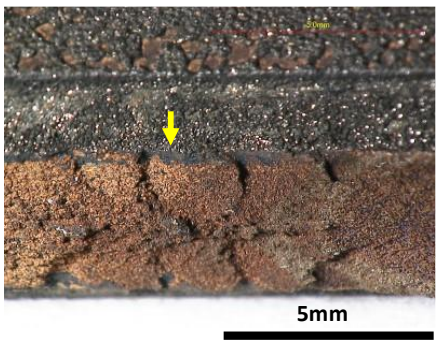
- Inspection was carried out using the setup as shown in the photo.
- Company A took pictures on the typical edge crack for each test specimen.
- Test specimens had been stored in atmospheric condition for about 1 month.

Results of Fracture surface evaluation

292



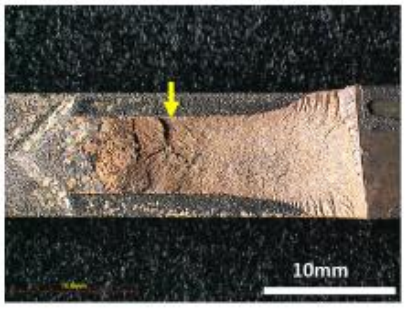
Note:
For enlargement of fracture surface, please see AMPP 2023 paper No.19218

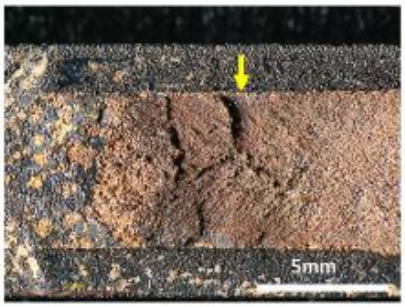


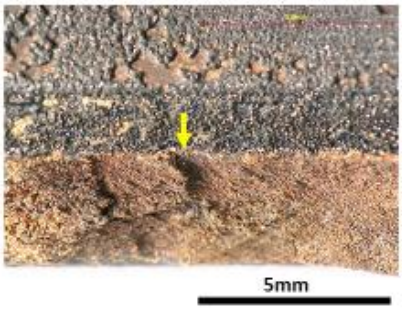
Invalid test specimen in accordance with 11.6.1 e) sub clause 3

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn = (a: 2.19mm) / (5.698mm) * 100 = 38.4%	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn = (b: 11.04mm) / (5.698mm) * 100 = 193.8%	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **= ((b: 11.04mm) /4 + (a: 2.19mm)) / (5.698mm) * 100 = 86.9 %**	Not exceed 25%

293





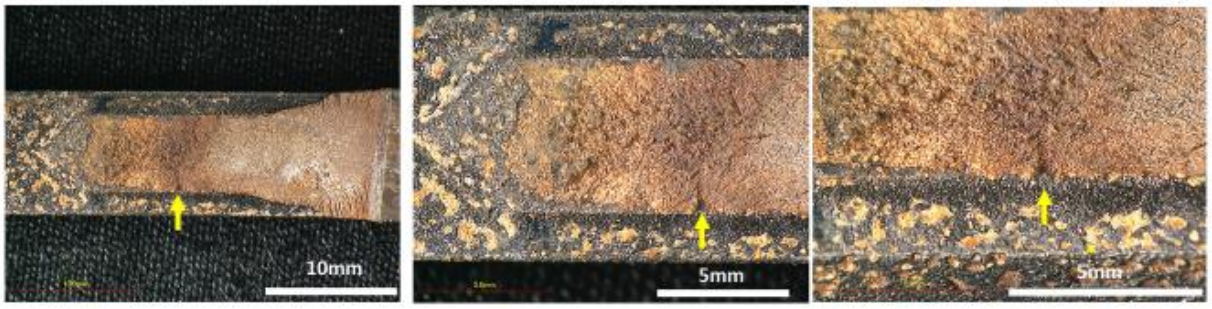


Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 4.00mm) / (5.676mm) * 100 = 70.5%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

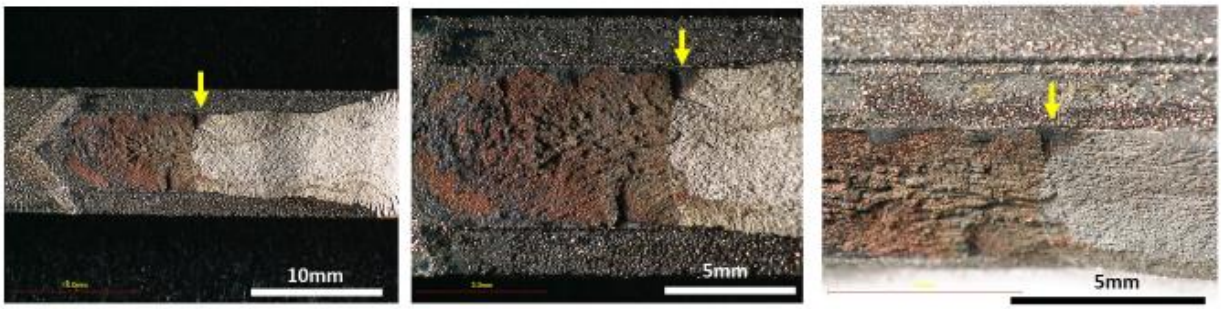
294



Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 2.03mm) / (5.677mm) * 100 = 35.8%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

295

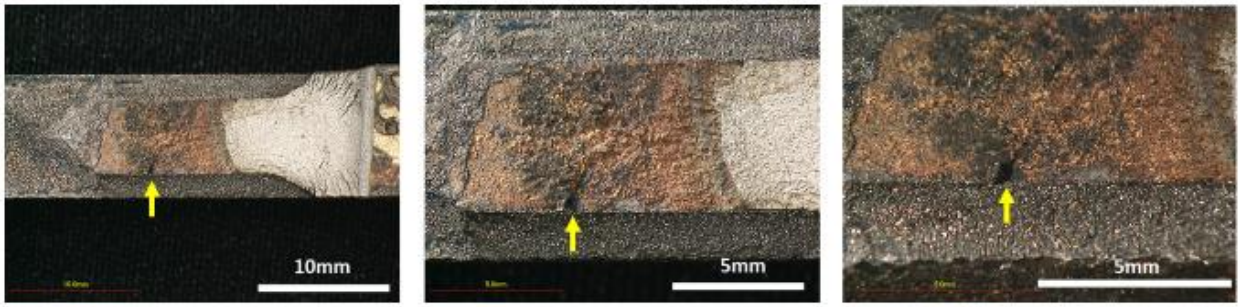


Invalid test specimen in accordance with 11.6.1 e) sub clause 3

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **= (a: 1.37mm) / (5.677mm) * 100 = 24.1%**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.76mm) / (5.677mm) * 100 = 31.0%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **= ((b: 1.76mm/4) + (a: 1.37mm)) / 5.677*100 = 31.9%**	Not exceed 25%

296



Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 2.23mm) / (5.637mm) * 100 = 39.6%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

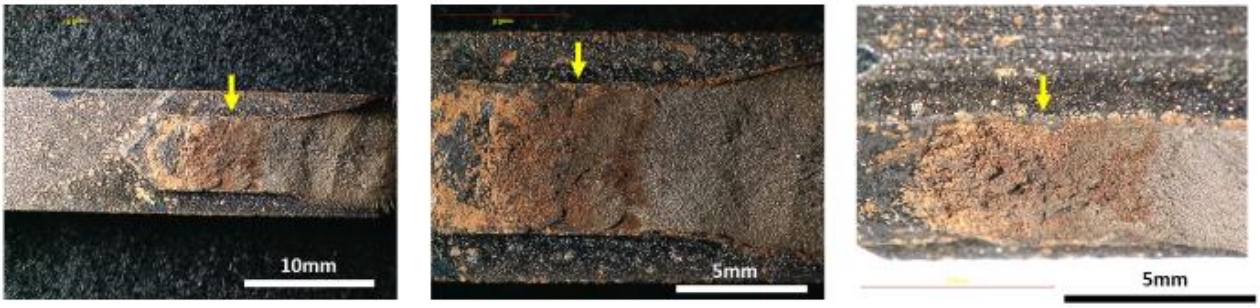
332

Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.02mm) / (5.674mm) * 100 = 18.0%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

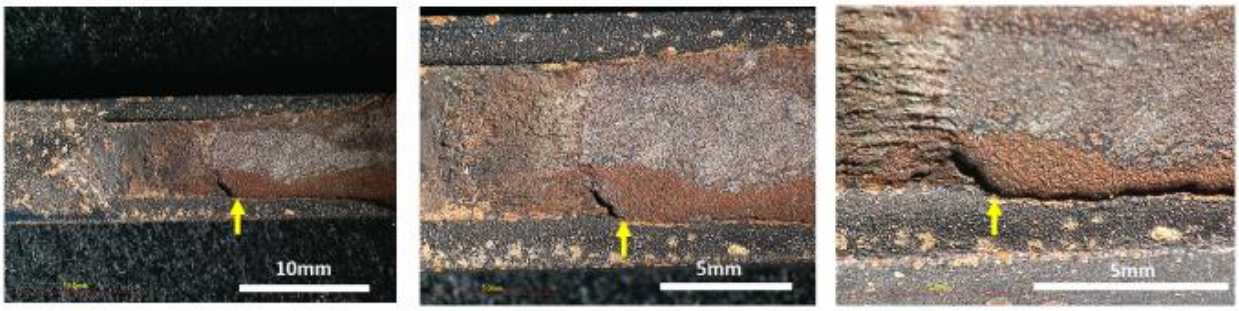
333



Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.86mm) / (5.621mm) * 100 = 33.1%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

334

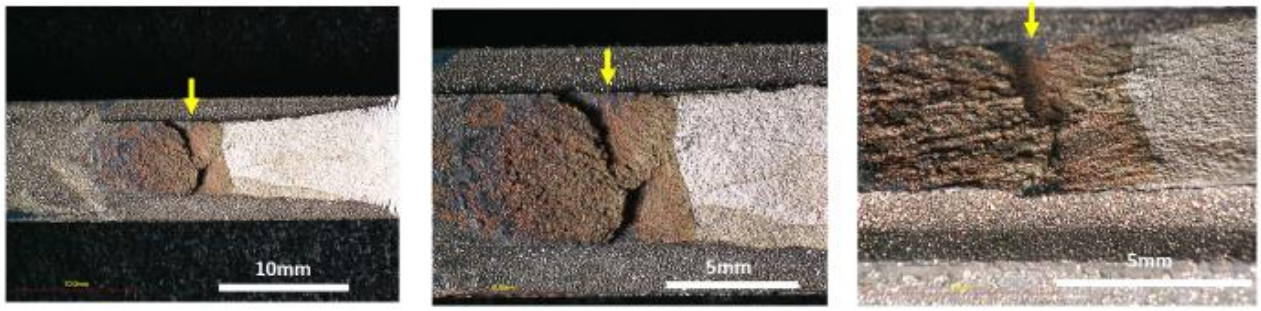


Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.96mm) / (5.669mm) * 100 = 34.6%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

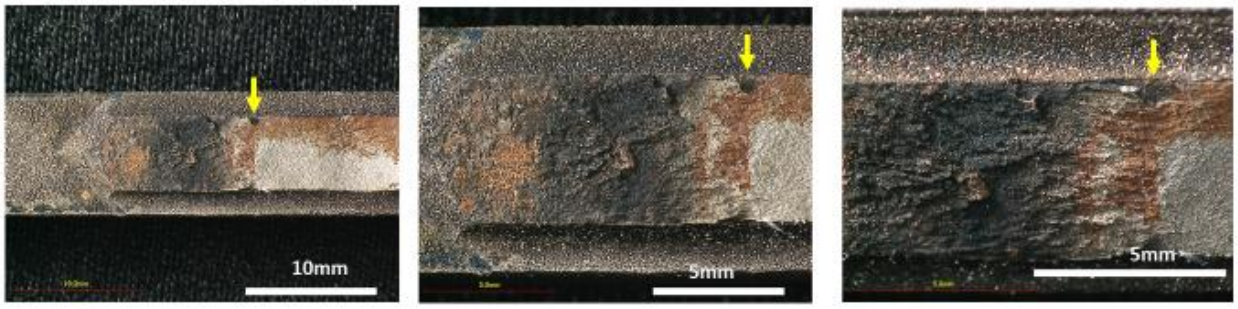
335



Valid test specimen in accordance with 11.6.1 e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 5.40mm) / (5.659mm) * 100 = 95.4%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

336

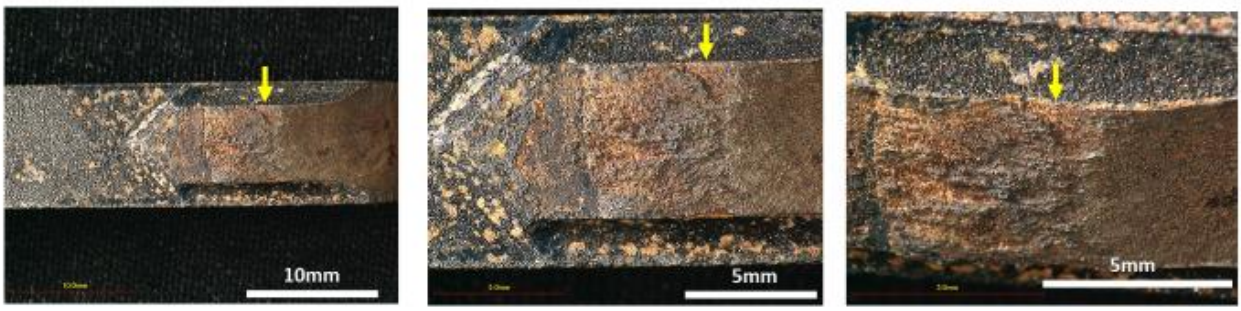


Invalid test specimen in accordance with 11.6.1 e) sub clause 3

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **= (a: 0.93mm) / (5.672mm) * 100 = 16.4%**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 2.91mm) / (5.672mm) * 100 = 51.3%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **= ((b: 2.91mm) /4 + (a: 0.93mm)) / (5.672mm) * 100 = 29.0 %**	Not exceed 25%

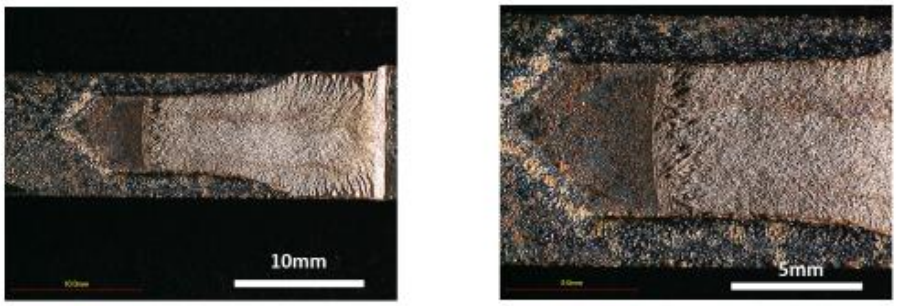
347



Valid test specimen in accordance with 11.6.1 (e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.43mm) / (5.740mm) * 100 = 24.9%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

348

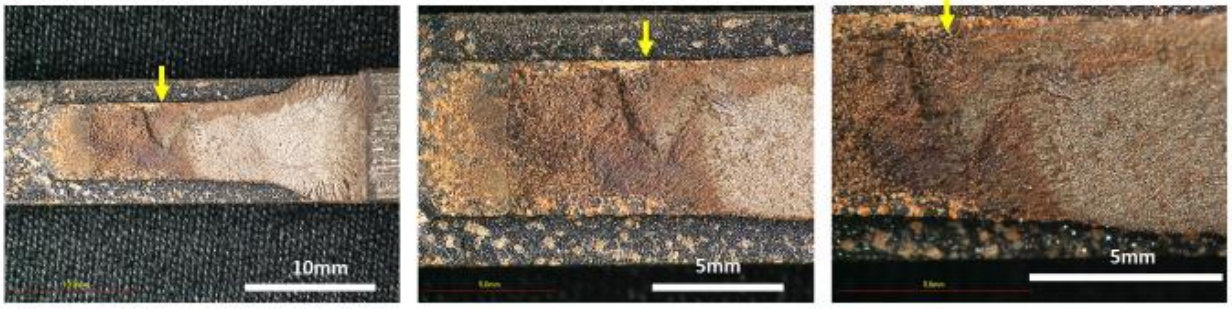


Invalid due to "short crack" in accordance with 11.6.1 (a)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

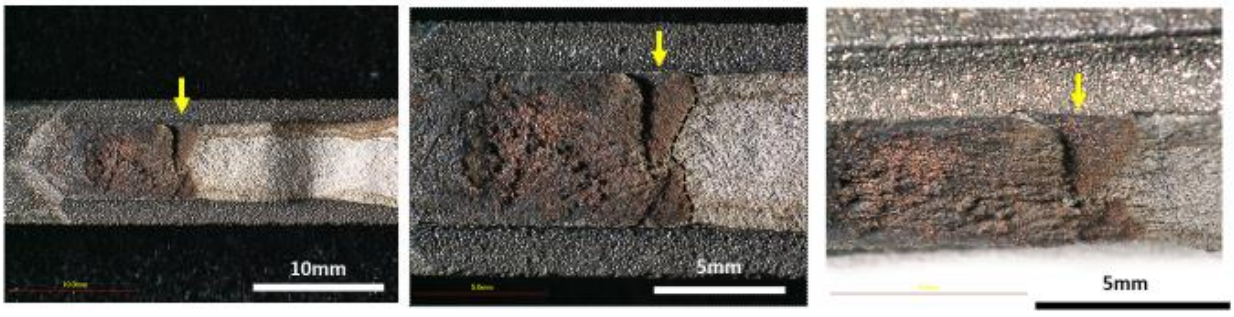
349



Valid test specimen in accordance with 11.6.1 (e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 3.62mm) / (5.742mm) * 100 = 63.0%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

350

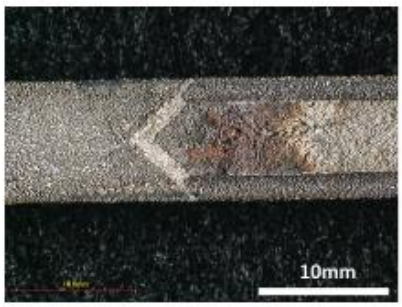


Valid test specimen in accordance with 11.6.1 (e)

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 4.77mm) / (5.696mm) * 100 = 83.7%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

351



Note:
For more enlargement of fracture surface, please see AMPP 2023 paper No.19218

Valid test specimen in accordance with 11.6.1 (e)

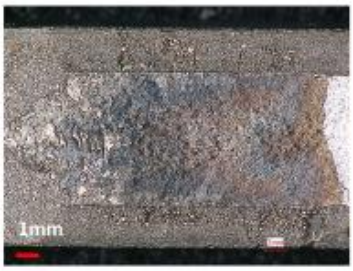
Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

(5) Fracture surface evaluation for verification using C110 with heavy wall in Sec. 5.3.2

Results of fracture surface evaluation

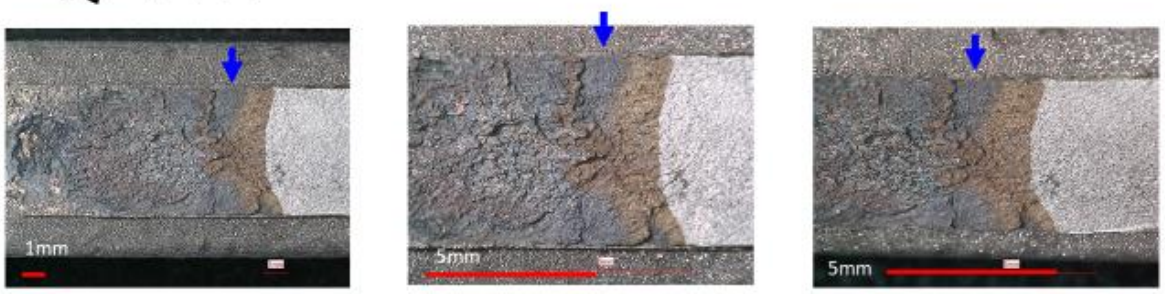
Fracture surface analysis for V shaped side groove with R0.25mm

QPT1-1



Validation in accordance with 11.6.1 (e)		Criteria
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT1-2



Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		Criteria
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 4.96mm) / (5.730mm) * 100 = 86.6%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT1-3

Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 3.78mm) / (5.734mm) * 100 = 65.9%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT1-4

Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 2.84mm) / (5.731mm) * 100 = 49.6%**	Not exceed 100%

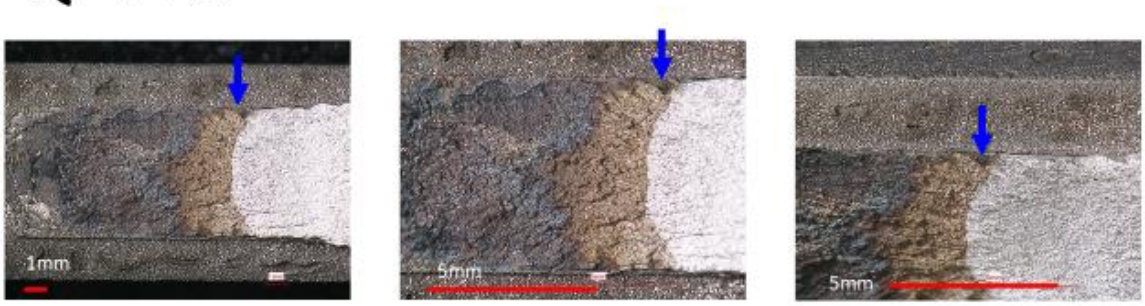
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT1-5

Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **= (a: 2.61mm) / (5.735mm) * 100 = 45.5%**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 3.29mm) / (5.735mm) * 100 = 57.4%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **= ((b: 3.29mm) /4+ (a: 2.61mm)) / (5.735mm) * 100 = 59.9 %**	Not exceed 25%

QPT1-6

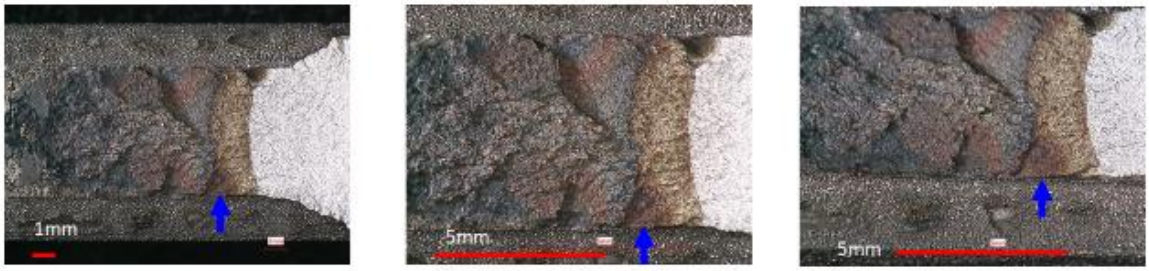


Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **= (a: 1.16mm) / (5.733mm) * 100 = 20.2%**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

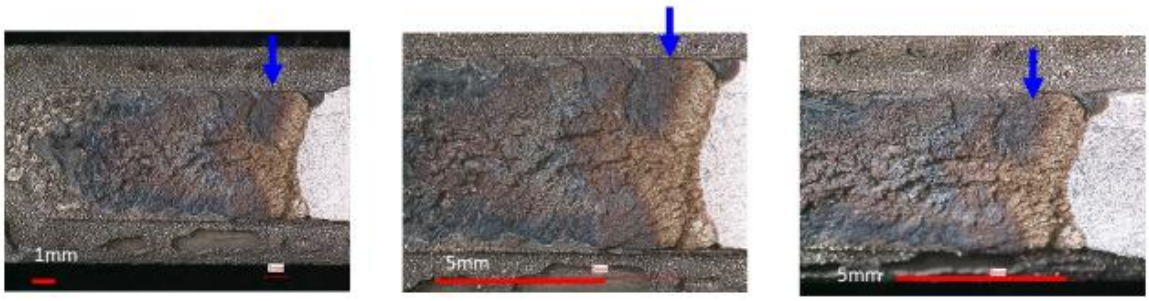
QPT1-7



Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 6.23mm) / (5.721mm) * 100 = 108.9%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT1-8

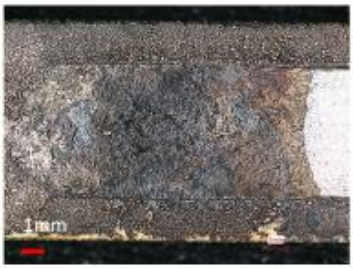


Blue arrow: The representative of edge crack revealed by low-angle illumination

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 2.42mm) / (5.716mm) * 100 = 42.3%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

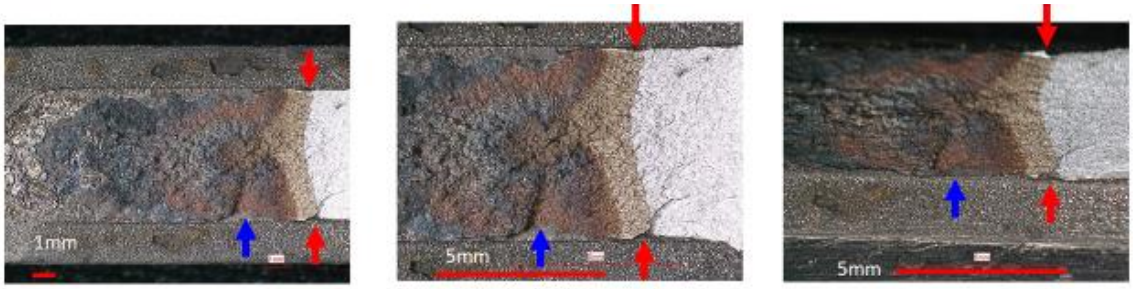
QPT1-9



Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT1-10

Blue arrow: The representative of edge crack revealed by low-angle illumination



The red arrows showed the edge cracks at the crack front.

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **= (a: 1.17mm) / (5.738mm) * 100 = 20.4%**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.53mm) / (5.738mm) * 100 = 26.7%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **= ((b: 1.53mm) /4 + (a: 1.17mm)) / (5.738mm) * 100 = 27.1 %**	Not exceed 25%

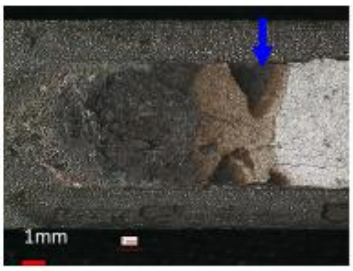
QPT1-11

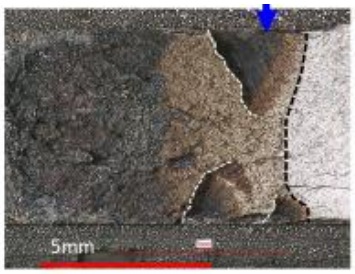
Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

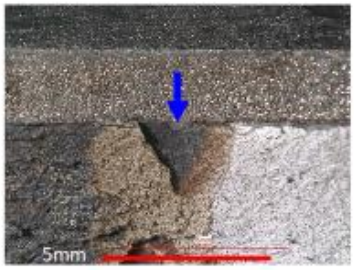
QPT1-12

Blue arrow: The representative of edge crack revealed by low-angle illumination

- Black dotted line: crack front line
- White dotted line: edge crack







All edge cracks was not on the crack front line. Therefore, edge cracks were calculated as the type of edge cracks lying away from the crack front.

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 4.32mm) / (5.747mm) * 100 = 75.2%**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

Fracture surface analysis for U shaped side groove with R0.65mm

QPT2-1

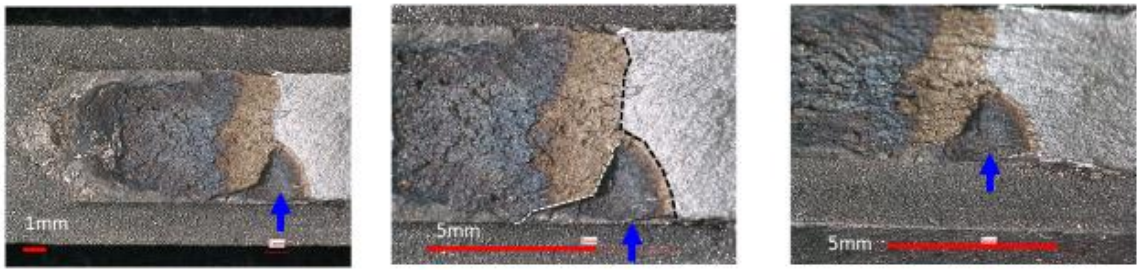
Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-2

Blue arrow: The representative of edge crack revealed by low-angle illumination

- Black dotted line: crack front line
- White dotted line: edge crack



Edge crack was not on the crack front line. Therefore, edge crack was calculated as the type of edge crack lying away from the crack front.

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 2.08mm) / (5.746mm) * 100 = 36.2%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT2-3

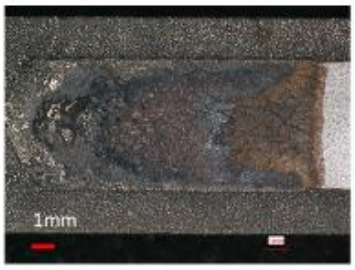
Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-4

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-5



Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-6

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

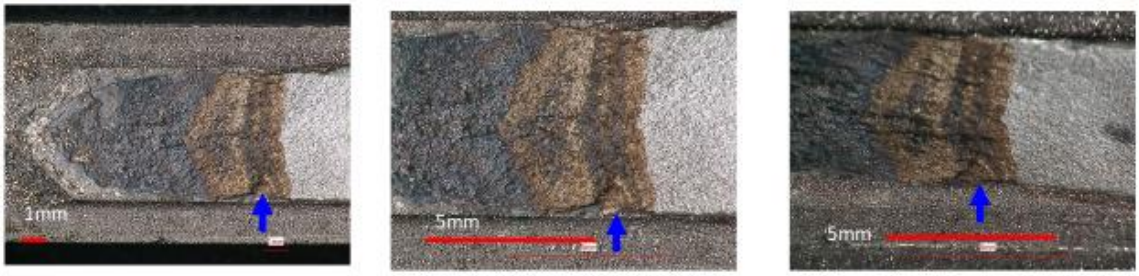
QPT2-7

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-8

Blue arrow: The representative of edge crack revealed by low-angle illumination



Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 0.47mm) / (5.749mm) * 100 = 8.2%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT2-9

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-10

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-11

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT2-12

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

Fracture surface analysis for U shaped side groove with R0.95mm

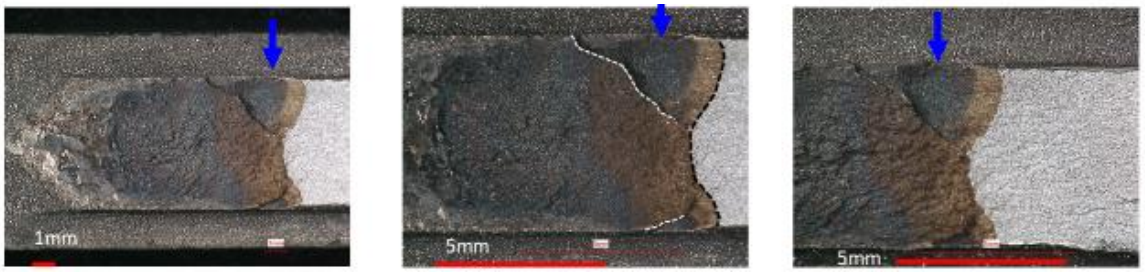
QPT3-1

Validation in accordance with 11.6.1 (e)		Criteria
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-2

Blue arrow: The representative of edge crack revealed by low-angle illumination

- Black dotted line: crack front line
- White dotted line: edge crack



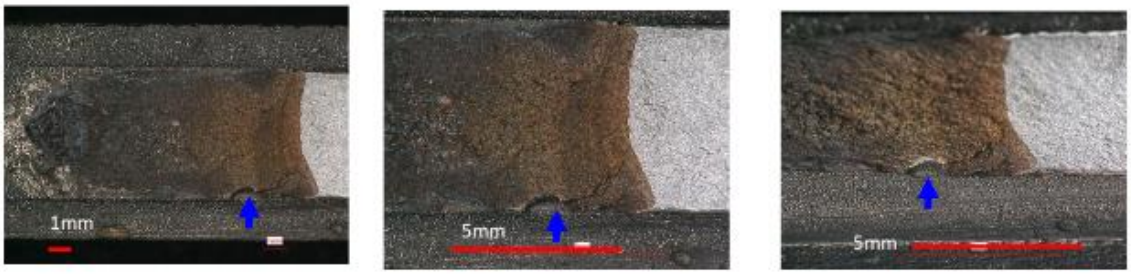
Edge cracks was not on the crack front line. Therefore, edge cracks were calculated as the type of edge cracks lying away from the crack front.

Validation in accordance with 11.6.1 (e)		Criteria
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 3.12mm) / (5.754mm) * 100 = 54.2%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT3-3

Blue arrow: The representative of edge crack revealed by low-angle illumination



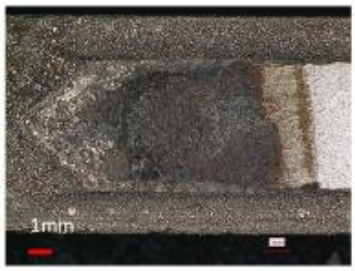
Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 0.79mm) / (5.752mm) * 100 = 13.7%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT3-4

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%

3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-5

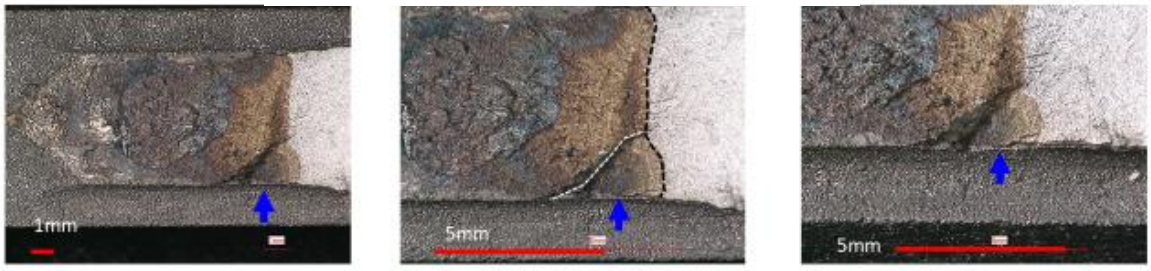


Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-6

Blue arrow: The representative of edge crack revealed by low-angle illumination

- Black dotted line: crack front line
- White dotted line: edge crack



Edge crack was on the crack front line.

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **= (a: 2.14mm) / (5.751mm) * 100 = 37.2%**	Not exceed 25%

2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 25%

QPT3-7

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-8

Validation in accordance with 11.6.1 (e)	**Criteria**

1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-9

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-10

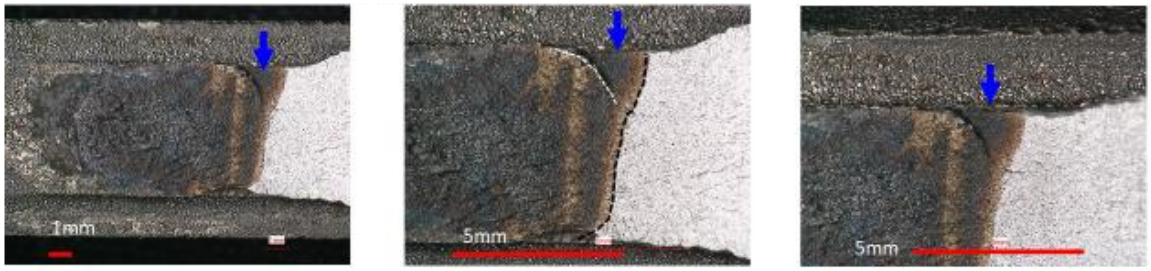
Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%

QPT3-11

Blue arrow: The representative of edge crack revealed by low-angle illumination

- Black dotted line: crack front line
- White dotted line: edge crack



Edge crack was not on the crack front line. Therefore, edge cracks were calculated as the type of edge crack lying away from the crack front.

Validation in accordance with 11.6.1 (e)		**Criteria**
1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **= (b: 1.57mm) / (5.756mm) * 100 = 27.3%**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks at crack front**	Not exceed 25%

QPT3-12

Validation in accordance with 11.6.1 (e)	**Criteria**

1	(a: Combined width of any crack front) / Bn **Note: no edge cracks at crack front**	Not exceed 25%
2	(b: Edge cracks lying away from the crack front that formed earlier in the test) / Bn **Note: no edge cracks lying away from the crack front**	Not exceed 100%
3	((b: the sum of the combined widths of the earlier-formed edge cracks) / 4 + (a: widths of those at crack front)) / Bn **Note: no edge cracks**	Not exceed 25%