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APPLICABILITY OF MINIATURE C(T) SPECIMEN TO EVALUATION OF FRACTURE TOUGHNESS FOR REACTOR PRESSURE VESSEL STEEL

Kentaro Yoshimoto
Mitsubishi Heavy Industries, Ltd.
Takasago R&D Center
Takasago, Japan

Takatoshi Hirota
Mitsubishi Heavy Industries, Ltd.
Kobe Shipyard & Machinery Works
Kobe, Japan

Hiroyuki Sakamoto
Mitsubishi Heavy Industries, Ltd.
Kobe Shipyard & Machinery Works
Kobe, Japan

Takuji Sugihara
Nuclear Development Corporation
Tokai, Japan

Shohei Sakaguchi
Kansai Electric Power Co., Inc.
Fukui, Japan

Toru Oumaya
Kansai Electric Power Co., Inc.
Fukui, Japan

ABSTRACT

Irradiation embrittlement of Japanese reactor pressure vessels (RPV) is usually monitored by conducting tests on irradiated RPV material according to surveillance test program. Although fracture toughness specimens are contained in Japanese PWR surveillance capsule, the number of specimens is limited due to capacity of capsule. In order to evaluate lower bound of fracture toughness considering its scatter with higher reliability, it is expected to obtain additional fracture toughness data using remaining broken specimens of irradiated materials.

One of solutions to this problem is specimen reconstitution technique. However, it is difficult to make numbers of specimens by reconstitution because of need for specific equipments and time-consuming machining operations. As an alternative method, fracture toughness test using miniature C(T) specimens with dimension of 4×10×10mm, which can be taken from broken halves of Charpy specimen, is proposed and the studies to verify the reliability and robustness of evaluation method have been conducted in the Japanese round robin program since 2010.

In this study, fracture toughness tests were performed on Japanese SA 533 Gr.B Cl.1 steel using miniature C(T) specimens and the effect of specimen size on reference temperature T_0 was studied by the Master Curve approach. In addition, the issues related to application to irradiated materials were discussed.

INTRODUCTION

Irradiation embrittlement of the Japanese RPV is monitored by the tests on the specimen of the RPV material irradiated based on the surveillance test program [1]. Although fracture toughness test specimens are contained in the Japanese PWR surveillance test capsule, the number of specimens is limited due to capacity of a capsule. For structural integrity evaluation of RPV, the lower bound curve, which enveloped limited fracture toughness data, is used in Japan. However, reliability of the curve can vary depending on the number of data and scatter. In recent years, the Master Curve approach has been developed as a method, which can express the confidence limit theoretically considering inherent statistical characteristic of fracture toughness. It has been adopted by the American Society of Mechanical Engineers standard [2, 3] and the International Atomic Energy Agency guideline [4]. In Japan, JEAC4216-2011 [5] which specifies the determination method of T_0 by the Master Curve approach was published in 2011. However, application of the method to structural integrity of RPV is now being discussed and under consideration. In order to evaluate lower bound of fracture toughness considering its scatter with higher reliability, it is expected to obtain additional fracture toughness data using remaining broken specimens of irradiated materials and evaluate reference temperature by the Master Curve approach.

It is effective in extension of fracture toughness database to utilize broken halves of Charpy specimen included in the surveillance test capsule in large numbers. Specimen reconstitution by welding can be a candidate to solve this problem [6]. However, it requires specific equipment and time-consuming machining operations for welding. Furthermore, only one three-point specimen can be made from a broken half of Charpy specimen to avoid the heat affected zone due to welding.

As an alternative to specimen reconstitution, fracture toughness test using 0.16TCT (miniCT) specimen, which has dimension of 4×10×10mm, was proposed. It has an advantage in fabrication from a broken Charpy specimen without welding. The studies to verify the reliability and robustness of evaluation method have been conducted in the Japanese round robin program since 2010 [7]. Since four miniCT specimens can be geometrically taken from a broken half of Charpy specimen [8], it will lead to effective use of remaining irradiated materials and reduction of cost by excluding welding.

As the existing ASTM standard (ASTM E1921-10$^{\varepsilon 1}$ [9]) does not limit the available specimen size, miniCT specimen can be used as is standardized. Therefore, it is important to check applicability to a smaller specimen such as miniCT, because the standard is based on fracture toughness data obtained by larger specimen.

For the above reasons, in this study, fracture toughness tests were performed on the Japanese RPV steel using two kinds of CT specimens. One of them is miniCT specimen, and the other one is 1/2TCT specimen, which currently used by the present surveillance test program. On the basis of test results, the effect of specimen size on reference temperature T_0 was studied by the Master Curve approach.

MATERIAL AND TEST METHOD

The Japanese PWR reference correlation material (SA533B Cl.1, thickness: 200 mm) was used in unirradiated state for this study. The material is placed in surveillance test capsules of some Japanese PWR plants for the purpose of comparison of irradiation embrittlement characteristic each other. The manufacturing process and heat treatment conditions of the material are shown in Table 1. 1/2TCT and miniCT specimens were taken so that specimen slit orientation was the same as the rolling direction of material (i.e. T-L direction). The chemical compositions and the tensile properties of the material at the room temperature are shown in Table 2 and Table 3, respectively. Fig. 1 and Fig. 2 illustrate the geometry and the dimensions of 1/2TCT and miniCT specimen, respectively.

Table 1 Manufacturing process and heat treatment conditions of material tested

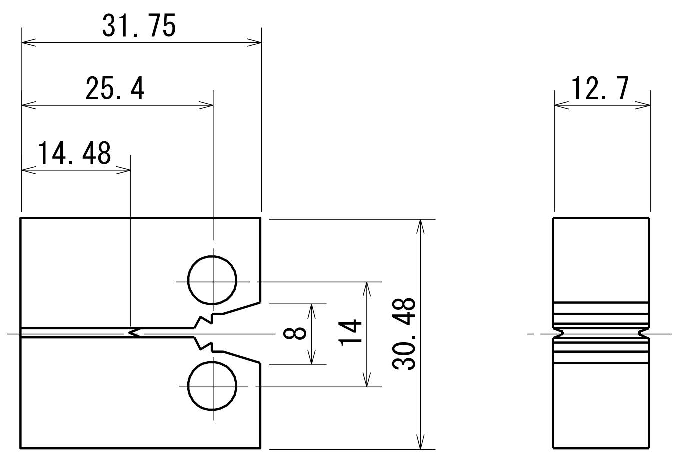
	Manufacturing conditions		
Manufacturing process	Dissolution → Ingot making → Rolling → Heat treatment		
Heat treatment condition	・ Normalizing	: 915～925℃×8.8Hr	Air cooling
	・ Tempering	: 655～660℃×11.9Hr	Air cooling
	・ Hardening	: 890～920℃×7.5Hr	Water cooling
	・ Tempering	: 660～690℃×7.1Hr	Air cooling
	・ Post weld heat treatment	: 608～615℃×13.5Hr	Furnace cooling

Table 2 Chemical compositions of the material tested

Material	Chemical compositions (wt%)			
	Si	P	Ni	Cu
Japanese PWR reference correlation material (SA533B Cl.1)	0.26	0.007	0.62	0.09

Table 3 Tensile properties at room temperature of the materials tested

Material	Temperature (℃)	Tensile properties			
		0.2% proof strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)
Japanese PWR reference correlation material (SA533B Cl.1)	23	499	637	23.2	67.2



Unit: in mm

Fig. 1 Geometry and dimensions of 1/2TCT specimen with side grooves

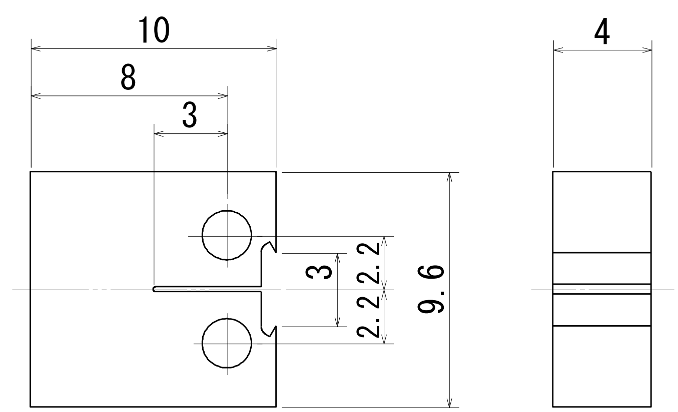


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Fig. 2 Geometry and dimensions of miniCT specimen

Tensile test specimens and 1/2TCT specimens were taken from 1/4T or 3/4T position, where miniCT specimens were machined from 1/4T position. Nine tensile test specimens, thirty-two miniCT specimens and twenty 1/2TCT specimens are machined from the material tested.

Fracture toughness tests were carried out at two or more temperatures close to T_0 using 1/2TCT and miniCT specimens. Table 4 listed temperature and number of specimens for fracture toughness tests.

Table 4 Temperature and number of specimens for fracture toughness tests

Temperature(℃)	Fracture toughness test	
	1/2TCT specimen	MiniCT specimen
-140	1	14
-125	15	4
-110	1	2
-95	15	—

Number denotes number of specimens

Fracture toughness test temperatures were chosen considering the temperature range ($T_0 \pm 50^{\circ}C$) in order to obtain valid fracture toughness data. The loading rate condition dK/dt was selected so as to be within the range of 0.1 to 2 MPa$\sqrt{m}$/sec during initial elastic portion, according to ASTM E1921-$10^{\varepsilon 1}$. Fracture toughness test data were evaluated in accordance with ASTM E1921-$10^{\varepsilon 1}$ which is basically equivalent to the Japanese standard JEAC4216-2011.

EVALUATION METHOD OF FRACTURE TOUGHNESS VALUE AND REFERENCE TEMPERATURE

The fracture toughness K_{Jc} was evaluated using Eqs. (1) to (5). The length of fatigue precrack was measured from the fracture surface after fracture toughness test, and validity was evaluated by Eqs. (6) to (9) with regard to K_{Jc} value, fatigue precrack length, and slow-stable crack growth extent.

＜The calculation of the fracture toughness K_{Jc}＞

$$K_{Jc} = \sqrt{J_c \frac{E}{1-\nu^2}} \quad (1)$$

$$J_c = J_e + J_p \quad (2)$$

The elastic component of J integral :

$$J_e = \frac{(1-\nu^2)\ K_e^{\ 2}}{E} \quad (3)$$

The plastic component of J integral :

$$J_p = \frac{\eta \cdot A_p}{B_N \cdot b_0} \quad (4)$$

$$K_e = \frac{P}{(B \cdot B_N \cdot W)^{1/2}} \cdot f\left(\frac{a_0}{W}\right) \quad (5)$$

$$f\left(\frac{a_0}{W}\right) = \frac{(2 + a_0/W)}{(1-a_0/W)^{3/2}}\left[0.886 + 4.64\left(\frac{a_0}{W}\right) - 13.32\left(\frac{a_0}{W}\right)^2 + 14.72\left(\frac{a_0}{W}\right)^3 + 5.6\left(\frac{a_0}{W}\right)^4\right]$$

E :Young's modulus (= 203 GPa)
where E was set constant for all the test temperature, because the temperature dependence data of E were not obtained for the material tested and it does not vary drastically below room temperature.

ν :Poisson's ratio (= 0.3)

η :η=2+0.522(b_0/W)

A_p : A_p=A-1/2C_0P^2 (C_0 is reciprocal of the initial elastic slope)

A : A = A_e (The elastic component of the area under a load-displacement curve) ＋ A_p (The plastic component of the area under a load-displacement curve)

B : Specimen thickness

B_N : The net thickness (the distance between the roots of the side groove notches in the case of side-grooved specimens)

b_0 : Initial ligament length (=W-a_0)

a_0 : Initial crack size, and

W : Specimen width

＜The validity condition of K_{Jc} ＞

$$K_{Jc} < K_{Jc(limit)} = \sqrt{\frac{E \cdot b_0 \cdot \sigma_{YS}}{30(1-\nu^2)}} \quad (6)$$

σ_{YS} : 0.2% proof strength

＜The validity conditions of fatigue precracking ＞

$$a_f \geqq \mathrm{Max}(0.5N,\ 0.6mm) \quad (7)$$

$$\Delta a_f \leqq \mathrm{Max}(0.05B,\ 0.5mm) \quad (8)$$

a_f : Fatigue precracking length (mm) (excluding notch length)

Δa_f : A difference with the average value of fatigue precracking (mm), and

N : Notch width (mm)

＜The validity condition of slow-stable crack growth＞

$$\mathrm{Max}(\Delta a_p) \leqq \mathrm{Min}(0.05(W-a_0),\ 1mm) \quad (9)$$

Δa_p : Slow-stable crack growth (mm)

TEST RESULTS

The tensile tests were carried out in order to obtain 0.2% proof strength required for validity evaluation of fracture toughness data. Tensile test results are summarized in Table 5. Fig. 3 shows temperature dependence of 0.2% proof strength and tensile strength.

Evaluation result of K_{Jc} value at each temperature based on result of fracture toughness test is listed in Table 6 and Table 7 for 1/2TCT and miniCT specimen, respectively. Fig. 4 and Fig. 5 indicate temperature dependence of fracture toughness for 1/2TCT and miniCT specimen, respectively. In addition, as a result of validity evaluation to the K_{Jc} value by Eq. (6), while all data (32 data) for 1/2TCT specimen were valid, 4 data of the 20 data about miniCT specimens were invalid.

Moreover, all the data for 1/2TCT specimen and miniCT specimen were valid as a result of the validity evaluation by Eqs. (7) and (8) regarding fatigue precrack length obtained by observation of fracture surface after test.

Validity was also checked for slow-stable crack growth extent by Eq. (9) when ductile crack growth is observed at fatigue precrack front of fracture surface. As a result, all the data were valid for 1/2TCT specimens, while only two data were invalid, and the others were valid for miniCT specimens.

Table 5 Tensile test results of Japanese PWR reference correlation material

Material	Temperature (℃)	Tensile test			
		0.2% proof strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction of area (%)
Japanese PWR reference correlation material (SA533B Cl.1)	-140	734	816	26.8	61.6
	-125	698	790	24.0	67.1
		679	786	24.6	66.9
	-110	646	767	27.0	61.8
	-95	625	748	23.8	65.1
		617	747	24.4	66.1
	R.T.(23)	499	637	23.2	67.2
	150	450	583	20.2	68.9
	300	440	614	20.4	61.5

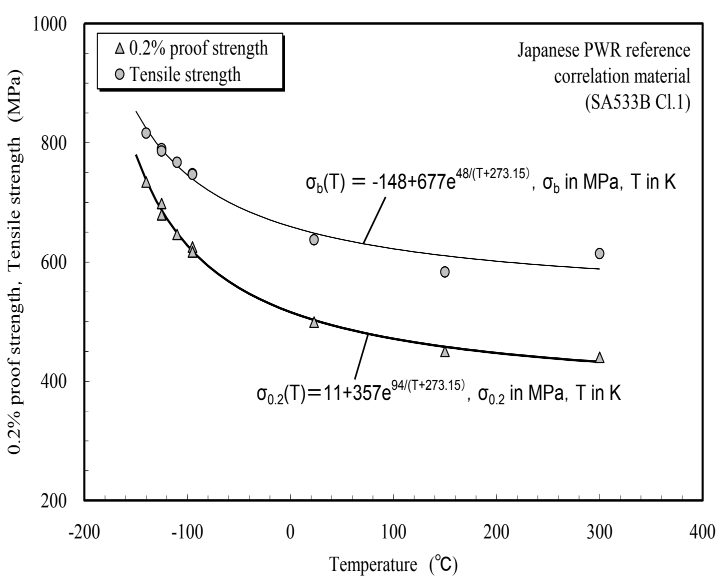

Fig. 3 Temperature dependence of 0.2% proof strength and tensile strength

Table 6 Fracture toughness test results of Japanese PWR reference correlation material (1 / 2TCT specimen)

Material	Temperature T (℃)	J_c (kJ/m^2)	Fracture toughness K_{Jc} (MPa√m)	1T equivalent K_{Jc} $K_{Jc(1T)}$ (MPa√m)	Validity of K_{Jc}
Japanese PWR reference correlation material (SA533B Cl.1)	-140	10.2	47.6	43.2	Valid
	-125	22.9	71.5	63.4	Valid
	-125	14.7	57.2	51.3	Valid
	-125	18.7	64.6	57.5	Valid
	-125	25.3	75.2	66.4	Valid
	-125	76.5	131	113	Valid
	-125	43.8	98.8	86.3	Valid
	-125	54.3	110	95.8	Valid
	-125	15.1	58.1	52.0	Valid
	-125	30.4	82.3	72.5	Valid
	-125	58.9	115	100	Valid
	-125	54.9	111	96.3	Valid
	-125	29.6	81.2	71.5	Valid
	-125	39.5	93.9	82.2	Valid
	-125	27.9	78.9	69.5	Valid
	-125	44.8	100	87.3	Valid
	-110	44.7	99.9	87.2	Valid
	-95	53.3	109	94.9	Valid
	-95	167	193	165	Valid
	-95	111	157	135	Valid
	-95	142	178	153	Valid
	-95	112	158	136	Valid
	-95	166	192	165	Valid
	-95	96.9	147	127	Valid
	-95	90.0	142	122	Valid
	-95	115	160	138	Valid
	-95	88.6	141	121	Valid
	-95	65.7	121	105	Valid
	-95	32.0	84.5	74.3	Valid
	-95	147	181	156	Valid
	-95	118	162	140	Valid
	-95	119	163	140	Valid

Table 7 Fracture toughness test results of miniCT specimen

Material	Temperature T (℃)	J_c (kJ/m^2)	Fracture toughness K_{Jc} (MPa√m)	1T equivalent K_{Jc} $K_{Jc(1T)}$ (MPa√m)	Validity of K_{Jc}
Japanese PWR reference correlation material (SA533B Cl.1)	-140	37.5	91.4	65.0	Valid
	-140	64.9	120.3	83.2	Valid
	-140	18.9	64.9	48.3	Valid
	-140	55.7	111.5	77.7	Valid
	-140	70.6	125.5	86.5	Valid
	-140	53.0	108.8	75.9	Valid
	-140	9.0	44.9	35.7	Valid
	-140	71.8	126.6	87.2	Valid
	-140	45.6	100.8	70.9	Valid
	-140	45.2	100.4	70.7	Valid
	-140	87.4	139.6	95.4	Valid
	-140	50.1	105.7	74.0	Valid
	-140	38.6	92.8	65.9	Valid
	-140	44.1	99.1	69.9	Valid
	-125	72.2	126.9	87.4	Valid
	-125	175.4	197.8	132.1	Invalid
	-125	319.7	267.1	175.7	Invalid
	-125	115.2	160.3	108.4	Invalid
	-110	49.2	104.8	73.5	Valid
	-110	205.7	214.2	142.4	Invalid

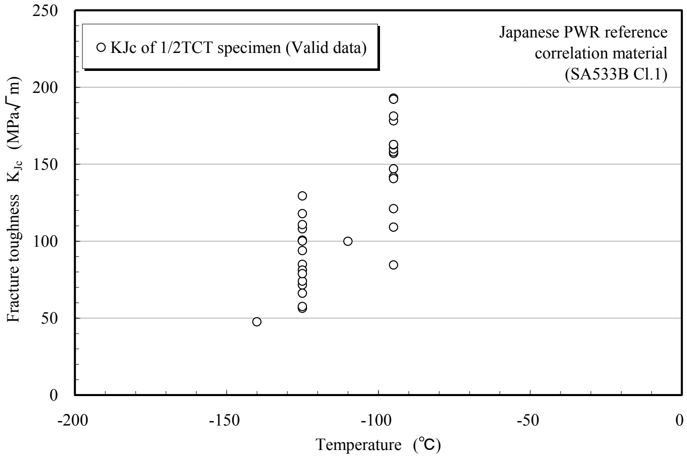

Fig. 4 Fracture toughness versus temperature for 1/2TCT specimen

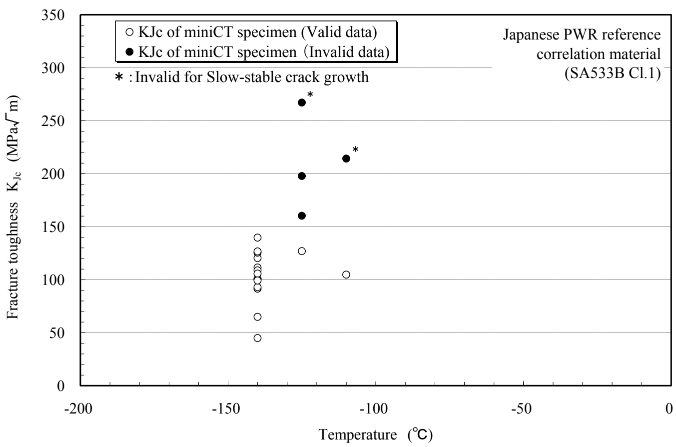

Fig. 5 Fracture toughness versus temperature for miniCT specimen

EVALUATION OF REFERENCE TEMPERATURE

The K_{Jc} value acquired by fracture toughness test was converted into 1T equivalent $K_{Jc}(K_{Jc(1T)})$ value by Eq. (10).

$$K_{Jc(x)} = K_{min} + [K_{Jc(O)} - K_{min}]\left(\frac{B_O}{B_x}\right)^{1/4} \tag{10}$$

$K_{Jc(O)}$: K_{Jc} for a specimen size B_O

B_O : Gross thickness of test specimen (side grooves ignored)

B_x : Gross thickness of prediction (side grooves ignored), and

K_{min} : 20 MPa√m

The $K_{Jc\ (1T)}$ values are shown in Fig. 6 and Fig. 7 for 1/2TCT specimens and miniCT specimens, respectively. The reference temperature T_0 was evaluated based on $K_{Jc(1T)}$ value. The invalid K_{Jc} value was replaced by either $K_{Jc(limit)}$ value for violation of $K_{Jc(limit)}$ or the highest valid K_{Jc} value for exceeding limitation on slow-stable crack growth. T_0 evaluated by multi-temperature method is -109°C for 1/2TCT specimen and -116 °C for miniCT specimen. These T_0 values are valid for the requirement of ASTM E1921. Additionally, T_0 was also evaluated by single-temperature method at -125 °C and -95 °C for 1/2TCT specimen and at -140°C for miniCT specimen. All the T_0 values are listed in Table 8 and compared with each other shown in Fig. 8. All the T_0 values are valid.

The difference in T_0 by multi-temperature method between 1/2TCT and miniCT specimen is approximately 7 °C. The maximum difference among all the T_0 values, which include ones by single-temperature method, is 9°C.

Consequently, the difference in T_0 was evaluated to be less than 10°C.

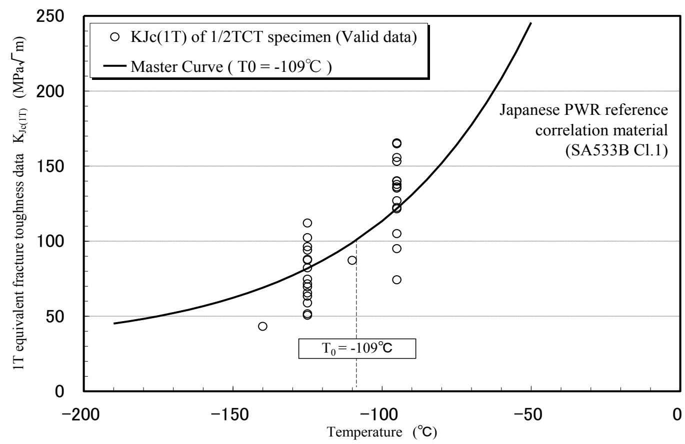

Fig. 6 Master Curve compared with 1T equivalent fracture toughness data for 1 / 2TCT specimen

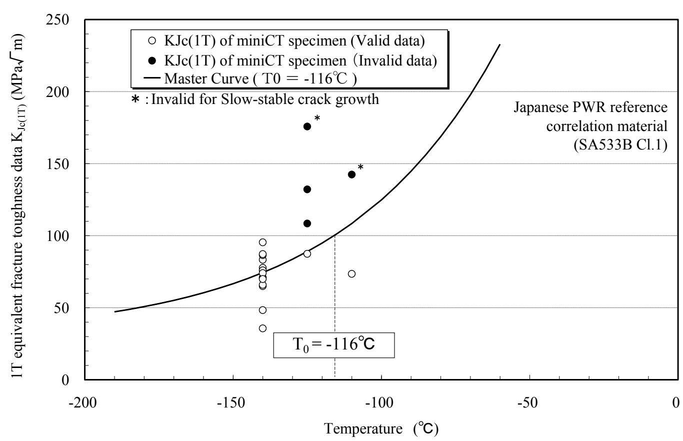

Fig. 7 Master Curve compared with 1T equivalent fracture toughness data for miniCT specimen

Table 8 Results of reference temperature T_0

TP Type	Evaluation Method	Temperature(℃)	Reference temperatureT_0	Number of total data (Number of valid data)	Validity of T_0
MiniCT specimen	Multi-Temp.	-140,-125,-110	-116	20 (16)	Valid
	Single-Temp.	-140	-113	14 (14)	Valid
1/2TCT specimen	Multi-Temp.	-140,-125,-110,-95	-109	32 (32)	Valid
	Single-Temp.	-125	-107	15 (15)	Valid
	Single-Temp.	-95	-112	15 (15)	Valid

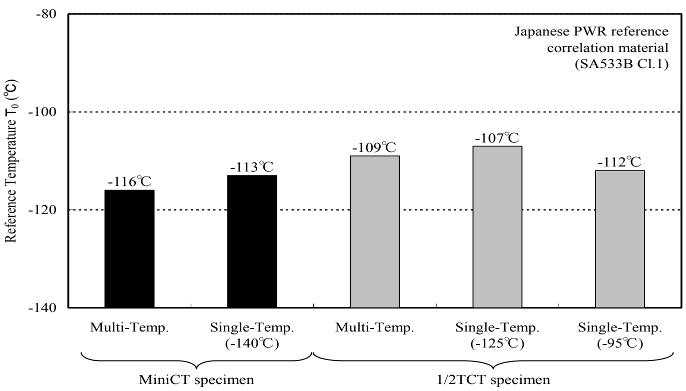

Fig. 8 Comparison of reference temperature T_0

DISCUSSION

Effect of specimen size on reference temperature T_0

In this study, the difference of T_0 between specimens with different size was 7°C. Therefore, by applying the Master Curve approach using $K_{Jc(1T)}$ converted from K_{Jc} by Eq. (10), T_0 by miniCT specimens seems to be equivalent to that by 1/2TCT specimens. According to the studies by Miura et al. [10, 11], a valid reference temperature T_0 does not affected by specimen size. This fact is in agreement with the result of this study which shows little difference in valid T_0 between 1/2TCT and miniCT specimen regardless of difference of evaluation method, i.e. single temperature and multi-temperature method. In addition, Miura et al. reported that this is common trend observed on the different materials which are SFVQ1A and SQV2A. Therefore, miniCT specimen can provide T_0 value equivalent to that for 1/2TCT specimen without addition of any specific margin if evaluated value is valid.

1/2TCT specimens used in this study were side-grooved whereas miniCT specimens were not. The difference can affect constraint of specimen. Ogawa et al. [12] analyzed Q-factor as the constraint parameter for these two types of specimens. They reported that there was little difference in Q-factor among these two types at the J-integral level, which cause brittle fracture of specimen.

From the above, miniCT specimen is very useful to evaluate fracture toughness of valuable irradiated materials.

Issues in application of miniCT specimen to irradiated materials

In order to apply the test method using miniCT to irradiated materials, it is necessary to fabricate and test miniCT specimen in radiation controlled area. Followings are the main issues to be discussed.

One of issues is concerning on accuracy of machining. The dimensional tolerances specified in ASTM E1921-10$^{\varepsilon 1}$ are shown in Table 9. According to this specification, dimensional tolerances are defined by the ratio to the specimen width W. For this reason, the dimensional tolerances for miniCT specimen are severe compared with 1/2TCT specimen. In such constraints, fabrication of specimen seems to be difficult in radiation controlled area using the limited existing equipments. Therefore, the fabricating method for miniCT specimens in radiation controlled area will be developed for satisfying the dimensional tolerance specified in the standard from now on. As a result, when the requirements specified in standard is difficult to be satisfied, it is necessary to consider whether it is possible to make dimensional tolerance looser.

The 2nd issue is related to fatigue pre-cracking. In general, the fatigue pre-crack length of miniCT specimen is shorter than that of 1/2TCT specimen. In this study, the fatigue pre-crack length of miniCT specimens was approximately 0.8 mm. When performing pre-cracking by remote control in radiation controlled area, it will be difficult to introduce fatigue pre-crack by monitoring on both sides of miniCT specimen. Therefore, progress of fatigue cracking must be monitored clearly, for example by using a high-resolution CCD camera, in order to control fatigue cracking length. In this process, parameters related to fatigue precracking, such as surface treatment conditions of specimen side surface, frequency, force control, shall be optimized adequately.

The 3rd issue is how many miniCT specimens are required to obtain valid T_0 value. When specimen size becomes smaller, the K_{Jc} value will become higher. In addition to that, the validity requirement for K_{Jc} will be difficult to be satisfied as the initial ligament size b_0 becomes smaller. For the effective use of valuable irradiated materials, it is required that valid T_0 can be obtained by the minimum number of miniCT specimens. In regard to this problem, Miura et al. [10] reported that valid T_0 would be obtained efficiently for miniCT specimen by choosing test temperature so that $T-T_0$ is within a range between -50°C and -30°C. In fact, all the data obtained at -140°C, i.e. $T-T_0$ is -24°C, were valid in this study and any slow-stable crack growth was not observed clearly. Therefore, if such a temperature could be chosen, it can be expected that valid T_0 value will be obtained by the miniCT specimen more efficiently and at lower cost than reconstituting to 1/2TCT specimen.

On the other hand, 0.2% proof strength will increase due to irradiation. It results in increase of $K_{Jc(limit)}$ value for irradiation materials compared with unirradiated materials. Consequently, it is expected that irradiated materials become easy to satisfy the validity requirements of K_{Jc} compared with unirradiated materials.

As an issue other than the above, it will be difficult to attach a clip gauge by remote control because the miniCT specimen is very small. It will be required to consider attachment procedure and develop an attachment device, etc.

By solving the above issues related to the miniCT specimen, fracture toughness data will be obtained for irradiated materials in radiation controlled area.

Table 9 Dimensional tolerances of CT specimen specified in ASTM E1921-10$^{\varepsilon 1}$

Principal dimensions	Specification in ASTM E1921-10$^{\varepsilon 1}$	miniCT specimen	1/2TCT specimen
Specimen width W	±0.005W	±0.04 mm	±0.127 mm
Specimen thickness B	±0.010W	±0.08 mm	±0.254 mm
Pin hole diameter φ	±0.005W	±0.04 mm	±0.127 mm

CONCLUSION

Fracture toughness tests according to ASTME1921-10$^{\varepsilon 1}$ were conducted on miniCT and 1/2TCT specimens fabricated from the Japanese PWR reference correlation material (SA533B Cl.1) in unirradiated state.

The difference in T_0 between miniCT and 1/2TCT specimen was less than 10°C . This result implies that miniCT specimen can provide T_0 value equivalent to that for 1/2TCT specimen without addition of any specific margin if evaluated value is valid.

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