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Mechanical properties of materials including fracture toughness are extremely important for evaluating the structural integrity of reactor pressure vessels (RPVs). In this report, the published data of mechanical properties of nuclear RPVs steels, including neutron irradiated materials, acquired by the Japan Atomic Energy Agency (JAEA), specifically tensile test data, Charpy impact test data, drop-weight test data, and fracture toughness test data, are summarized. There are five types of RPVs steels with different toughness levels equivalent to JIS SQV2A (ASTM A533B Class 1) containing impurities in the range corresponding to the early fission reactor plants to the latest plants. Neutron irradiation test was conducted at Japan Material Testing Reactor (JMTR). The data of the neutron fluence up to about 1×10^{20} n/cm^2 (E>1 MeV) at 290ºC±5ºC was evaluated. In addition to the base material of RPVs, the mechanical property data of the two types of stainless overlay cladding materials used as the lining of the RPV are summarized. These mechanical property data are summarized graphically for each material and listed also in tabular form to facilitate easy utilization of data.

Keywords: Reactor Pressure Vessel Steel, Stainless Overlay Cladding, Neutron Irradiation, and Mechanical Property

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原子炉圧力容器鋼の破壊靭性評価に係る機械的特性データ集

日本原子力研究開発機構
安全研究・防災支援部門　安全研究センター　材料・構造安全研究ディビジョン

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原子炉圧力容器の健全性を判断する上で、破壊靭性を始めとする材料の機械的特性は重要な情報となる。本レポートは、日本原子力研究開発機構が取得した中性子照射材を含む原子炉圧力容器鋼材の機械的特性、具体的には引張試験、シャルピー衝撃試験、落重試験及び破壊靭性試験の公開データをまとめたものである。対象とした材料は、国内の初期プラントから最新プラントに相当する範囲の不純物含有量及び靭性レベルで製造された 5 種類の原子炉圧力容器鋼である(JIS SQV2A(ASTM A533B Class1)相当)。中性子照射試験は Japan Material Testing Reactor (JMTR)にて実施された。照射量は最大で約 1×10^{20} n/cm^2(E>1 MeV)、照射温度は 290ºC±5ºC である。また母材に加え、原子炉圧力容器の内張りとして用いられている 2 種類のステンレスオーバーレイクラッド材の機械的特性データについても掲載した。これらの機械的特性データは、材料ごとにグラフで整理するとともに、今後データを活用しやすいように表形式で整理した。

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1. Introduction

Since the reactor pressure vessels (RPV) are primary coolant boundary components, ensuring the structural integrity of RPVs is extremely important. In the transition temperature region, the fracture toughness of RPV steel depends on temperature, and fracture toughness decreases with decreasing temperature.

Because high pressure and low temperature are superimposed in RPV at the operating transients, such as startup/shutdown of nuclear reactor operations and pressurized thermal shock event, if there are defects such as cracks on the inner surface of the RPV, they may penetrate the vessel. By subjected to neutron irradiation from the core, the fracture toughness of RPV steel gradually decreases and the transition temperature is shifted to high temperatures. Therefore, as reactor operation duration is prolonged, these property changes can be seriously affected on the structural integrity of RPV. Thus, evaluating the fracture toughness of RPV steel under the operation service is very important.

Recently, the Master Curve (MC) method has been developed to evaluate the temperature dependence of fracture toughness by conducting a relatively small number (6~8 or more) of fracture toughness tests and tensile tests[1-1, 1-2)]. In the MC method, the temperature dependence of the median value of fracture toughness distribution of a 1-inch-thickness compact tension-type (1T-C(T)) specimen is provided by a single exponential curve. This concept, developed by Wallin et al. [1-3)], accounts successfully for size effects on fracture toughness by combining the weakest link size effect with micro-mechanical models of cleavage fracture, and provides a means to calculate statistical confidence bounds on cleavage fracture toughness data.

In Japan Atomic Energy Agency (JAEA), many tests including irradiation tests related to fracture toughness evaluation of RPV steels by the MC method have been performed, and their results were published. The present report summarizes the published data of mechanical property for unifying relevant data pertaining to fracture toughness evaluation of RPV steels, including the data acquired at the Japan Atomic Energy Research Institute from 1994[1-4, 1-5, 1-6)]. The materials are the RPV steels based on the JIS SQV 2 A (ASTM A 533 B Class 1) standard. We focused on impurities in the steels that are thought to influence irradiation embrittlement considerably and the chemical compositions adjusted the contents of phosphorus, sulfur, and copper, as well as the toughness level. With the progress of manufacturing technology of reactor pressure vessel, the content of copper, phosphorus and sulphur contents in RPV steel has been gradually decreased. In the surveillance data of the base materials of the PWR plants in Japan, the phosphorus and the copper contents are distributed in 0.014 to 0.003 % and 0.16 to 0.018 %, respectively[1-7)].

In addition to the unirradiated material, we examined the materials that were subjected to high levels of neutron irradiation (up to about 10^{20} n / cm^2 (E>1 MeV)) at the Japan Materials Testing Reactor (JMTR). Fracture toughness data obtained from specimens of different dimensions were summarized. The specimen sizes ranged from large compact tension-type (4T-C(T)) with a thickness of 100 mm to small compact tension-type (Mini-C (T)) with a thickness of 4 mm that can be taken from a Charpy impact specimen. In addition, the data of tensile tests, drop-weight tests, and Charpy impact tests were collected and analyzed as mechanical properties related to fracture toughness evaluation. By contrast, stainless steel overlay cladding of about 5 mm in thickness was welded to the inner surface of the RPV, and the mechanical properties of the cladding were considered in the structural integrity assessment[1-8)]. Therefore, mechanical property data of the cladding were also described. These mechanical property data of each material are summarized and presented in graphical and tabular formats.

The data summarized in this research report will be useful to the structural integrity assessments of RPVs and evaluation of irradiation embrittlement of RPV steels. Material test data are listed in Table 1.

Table 1 List of materials and test data

(σ_y: Yield strength; σ_u: Ultimate strength; T_{NDT}: Nil-ductility transition temperature)

Material ID		Fluence*[1] (10^{19} n/cm^2) E>1 MeV	Tensile test		Charpy impact test	Drop-weight test	Fracture toughness test*[2]				
			Temperature dependence of σ_y and σ_u	Stress-crosshead displacement curve	Charpy transition curve	T_{NDT}	Mini-C(T)	PCCv*[3]	0.4T-C(T)	1T-C(T)	4T-C(T)
RPV steels	Steel A	0	○	○	○	○	○	○		○	○
		9-13	○		○			○			
	Steel B	0	○	○	○	○	○	○		○	○
		8-11	○		○			○			
	JRQ	0			○		○	○	○	○	
		2-11			○			○			
	Steel L	0	○		○					○	
		2.9-3.1	○		○						
	JSPS	0	○		○			○			
Stainless steel overlay cladding	SAW CL	0	○	○	○						
		10-12	○	○	○						
	ESW CL	0	○	○	○						
		12-15	○	○	○						

*[1] These irradiation tests were conducted in the JMTR.

*[2] Fracture toughness tests using Mini-C (T) specimens and other (PCCv, 0.4T-C(T) , 1T-C(T)) specimens were conducted according to ASTM E 1921-12 and ASTM E 1921-97, Respectively.

*[3] Pre-Cracked Charpy-v type specimen (PCCv).

2. Fabrication of material used

Five types of ASTM A533B Class 1 steel (Steel A, Steel B, JRQ, Steel L and JSPS) plates of thickness about 200 mm were fabricated according to JIS SQV 2 A and ASME SA533/SA533M (except Cu, P, and S contents) [2-1]. Here, JRQ is the International Atomic Energy Agency (IAEA) "reference" material used in several IAEA coordinated research programs[2-2]. JRQ is used for many IAEA projects dealing with the study of the behavior of RPV steels under neutron irradiation, which began in 1983. The use of JRQ material has since then been internationally recognized and explored by a number of Member States. JSPS is the material used in the round robin study organized by The Japan Society for Promoting of Science (JSPS) [2-3]. This material was deliberately embrittled by increasing the concentration of Sulphur and Phosphorous in order to obtain a very low Upper Shelf Energy (USE ≈ 70 J) in the unirradiated condition.

The heat treatment for these steels were carried out according to the standard. As an example, the heat treatment conditions of Steel A, Steel B, JRQ and Steel L are shown in Table 2.

Two types of weld overlay cladding materials were fabricated by means of submerged-arc welding (SAW CL) and electroslag welding (ESW CL) of base metals with stainless steel plates, respectively [2-4]. The thickness of the both cladding was about 5 mm and heat treatment was carried out for 7 hours at 615 ºC ± 20 ºC after welding. The dimensions of the base metal used for welding are 850 mm × 550 mm × 200 mm thickness.

Table 3 shows the chemical compositions of the materials taken from the 1/4 thickness position of the plates and cladding materials.

Table 2 Heat treatment of Steel A, Steel B, JRQ and Steel L

Material ID	Quenching	Tempering	Stress relief
Steel A	860 to 893 ºC, Water quenched	650 to 660 ºC – 6 h, Air cooled	610 to 623 ºC – 42 h, Cooling rate <-35ºC/h
Steel B	860 to 893 ºC, Water quenched	650 to 660 ºC – 6 h, Air cooled	610 to 623 ºC – 42 h, Cooling rate <-35ºC/h
JRQ	880 ºC, Water quenched	665 ºC – 12 h, Air cooled	620 ºC – 40 h
Steel L	900 ºC, Water quenched	660 ºC – 5 h, Air cooled	600 ºC – 25 h Cooling rate < -50 ºC/h

Table 3 Chemical composition (wt %) of materials

Material ID		C	Si	Mn	P	S	Cu	Ni	Cr	Mo
Steel A		0.19	0.30	1.30	0.015	0.010	0.16	0.68	0.17	0.53
Steel B		0.19	0.19	1.43	0.004	0.001	0.04	0.65	0.13	0.50
JRQ		0.18	0.24	1.42	0.017	0.004	0.14	0.84	0.12	0.51
Steel L		0.17	0.24	1.36	0.003	0.003	0.02	0.61	0.07	0.47
JSPS		0.24	0.41	1.52	0.028	0.023	0.19	0.43	0.08	0.49
SAW CL (Base: Steel A)	First layer: SUS309L	0.058	0.57	1.49	0.013	0.008	—	9.9	19.5	0.08
	Last layer: SUS308L	0.030	0.84	1.56	0.009	0.009	—	10.4	19.6	0.01
ESW CL (Base: Steel B)	First layer: SUS309L	0.013	0.62	1.28	0.02	0.002	—	10.7	19.5	0.02
	Last layer: SUS308L	0.013	0.65	1.18	0.02	0.002	—	10.7	19.5	0.02

3. Tensile test

3.1 Test procedure

Tensile tests, in which two types of test specimens were examined, were conducted in the temperature range from -200 °C to 290 °C. The test temperature was measured with a K type thermocouple in contact with the specimen. The tensile test was carried out using Shimadzu or Instron's universal testing machine. In the tests, the crosshead speed was 0.1~0.5 mm/min at the constant. Schematic images of the specimens are shown in Fig. 3.1-1. Note that the SS - 3 type specimens tend to exhibit yield stress and tensile strength as high as several % and elongation as low as several %, as compared with round bar type specimens. The series of specimens were taken in the T direction from the 1/4 thickness position of the steel plate.

3.2 Results

Tensile tests were conducted using unirradiated materials (Steel A, Steel B, JRQ, Steel L, JSPS, SAW CL and ESW CL) and irradiated materials (Steel A, Steel B, Steel L, SAW CL and ESW CL). The stress-crosshead displacement curves obtained at the temperature examined are shown in Fig. 3.2-1, and the corresponding tensile test results (yield strength (σ_y), ultimate strength (σ_u), uniform elongation, fracture elongation, total elongation, and reduction of area) are summarized in Table A of Appendix. Figure 3.2-1 and Figure 3.2-2 shows the stress-crosshead displacement curves and the temperature dependence of tensile properties, respectively. Here, the graph of JRQ is a reprint of the one of IAEA report [3-1].

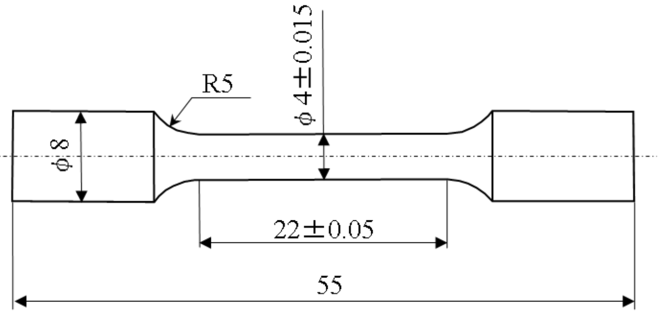
The σ_y measured (σ_y(meas.)) in the present study was compared to the calculated temperature dependence of σ_y ($\sigma_{y(cal.)(T)}$), and the comparison result is shown in Fig. 3.2-3. The $\sigma_{y(cal.)(T)}$ was calculated using the following equation given in the Japan Welding Engineering Society Standards (WES1108-1195). This equation is also recommended as yield stress evaluation method of the Japanese Electric Association Code"Test Method for Determination of Reference Temperature, T_o, of Ferritic Steels," (JEAC 4216-2015).

$$\sigma_{y(cal.)(T)} = \sigma_{y(RT)}\exp\left\{\left[481.4 - 66.5\ln\left(\sigma_{y(RT)}\right)\right]\left[\frac{1}{T+273} - \frac{1}{293}\right]\right\} \qquad (3\text{-}1)$$

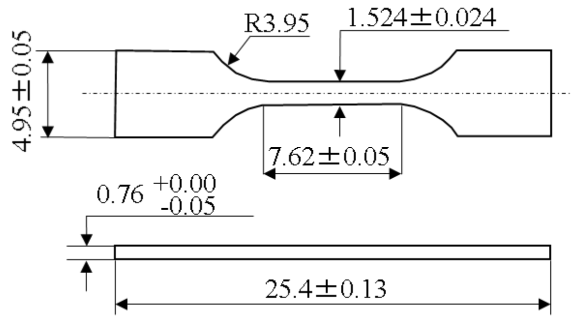
Here, $\sigma_{y(RT)}$ is the σ_y value at room temperature (in MPa), T is temperature (in K).

In Fig. 3.2-3, the evaluation results of the material JRQ using literature data [2-2] of σ_y(meas.) are plotted as well. From Fig. 3.2-3, σ_y(cal.) is almost equal to σ_y(meas.) at temperatures above 0 °C, whereas σ_y(cal.) is smaller than σ_y(meas.) at temperatures below 0 °C.

(Round bar type: Steel A, Steel B, Steel L, JSPS, SAW CL and ESW CL)

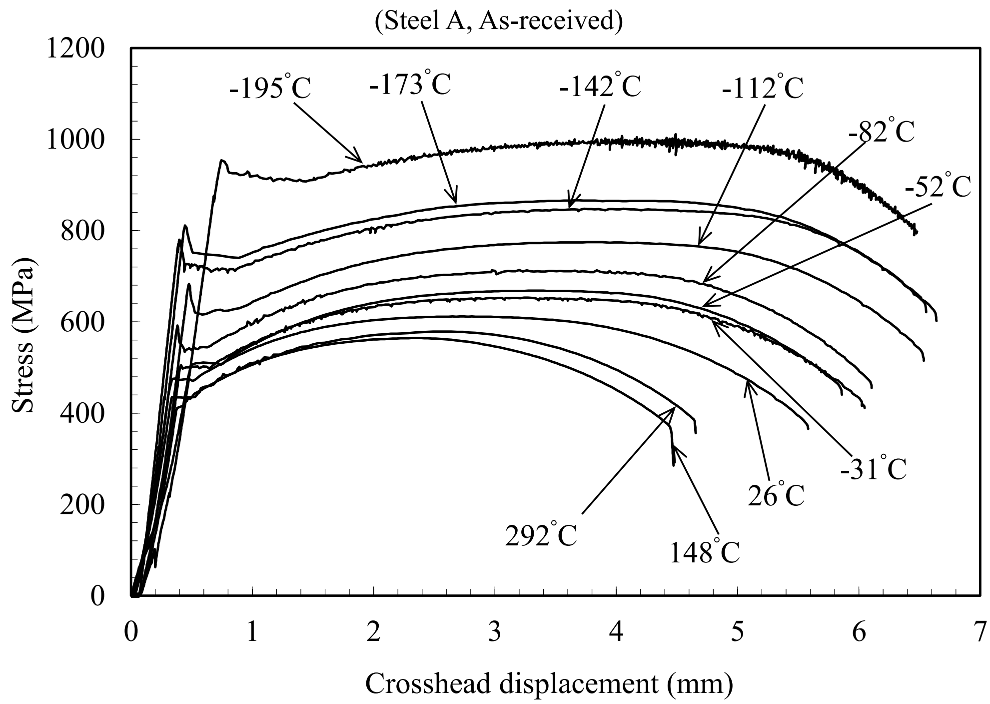


(SS-3 type: SAW CL, ESW CL)



(mm)

Fig. 3.1-1 Schematic images of tensile test specimens



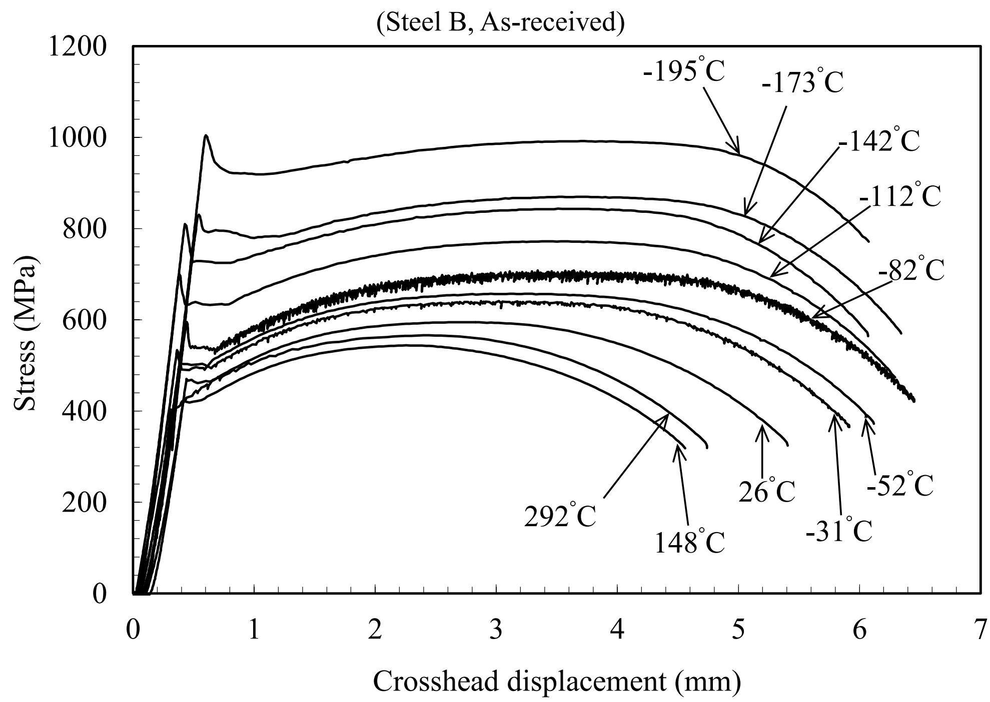
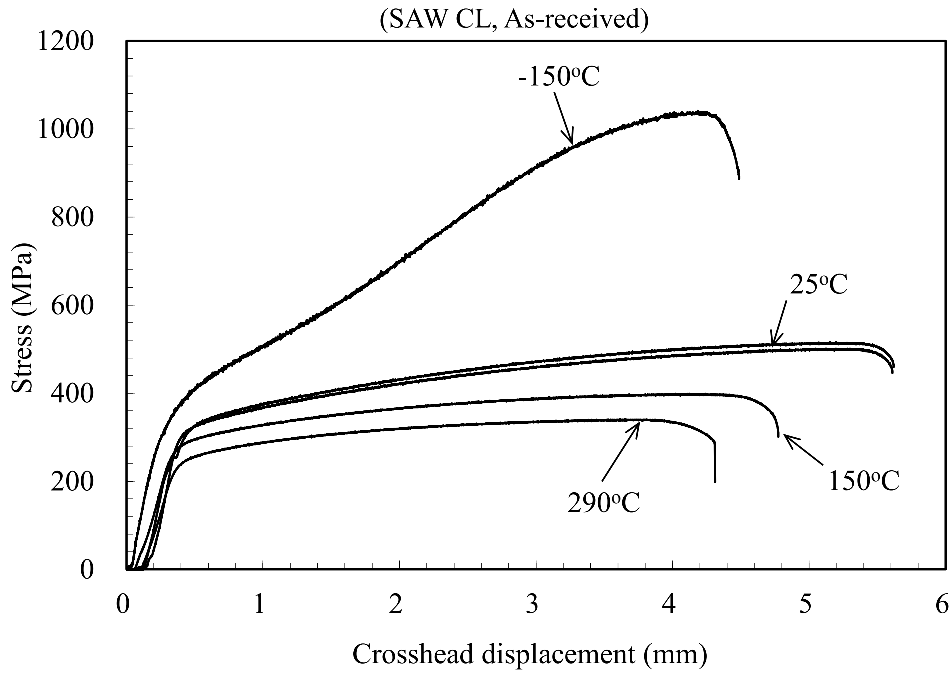


Fig.3.2-1　Stress-crosshead displacement curves (1/3)



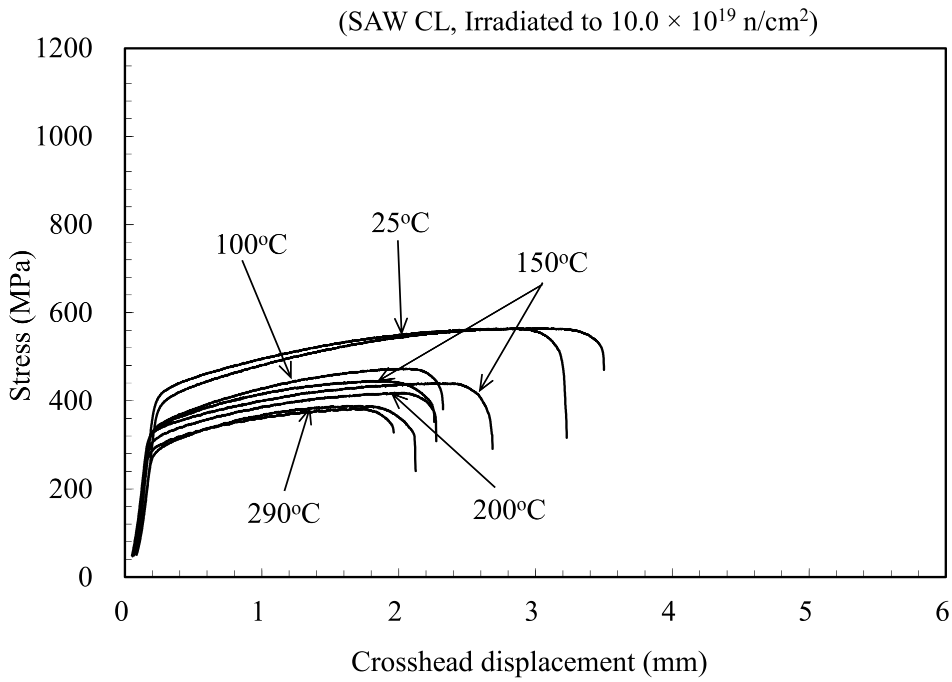
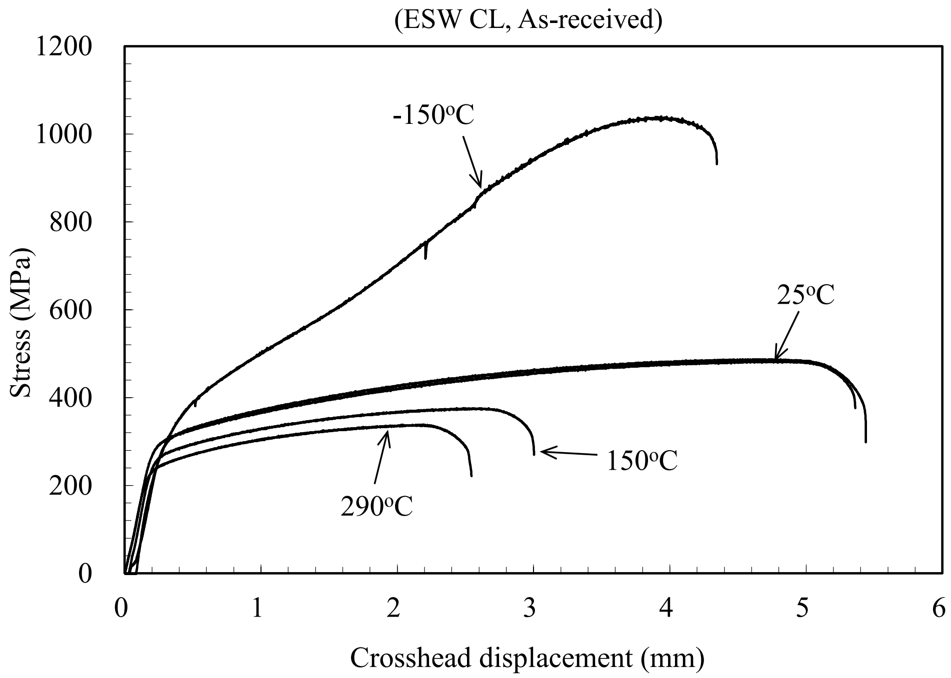


Fig.3.2-1 Stress-crosshead displacement curves (2/3)



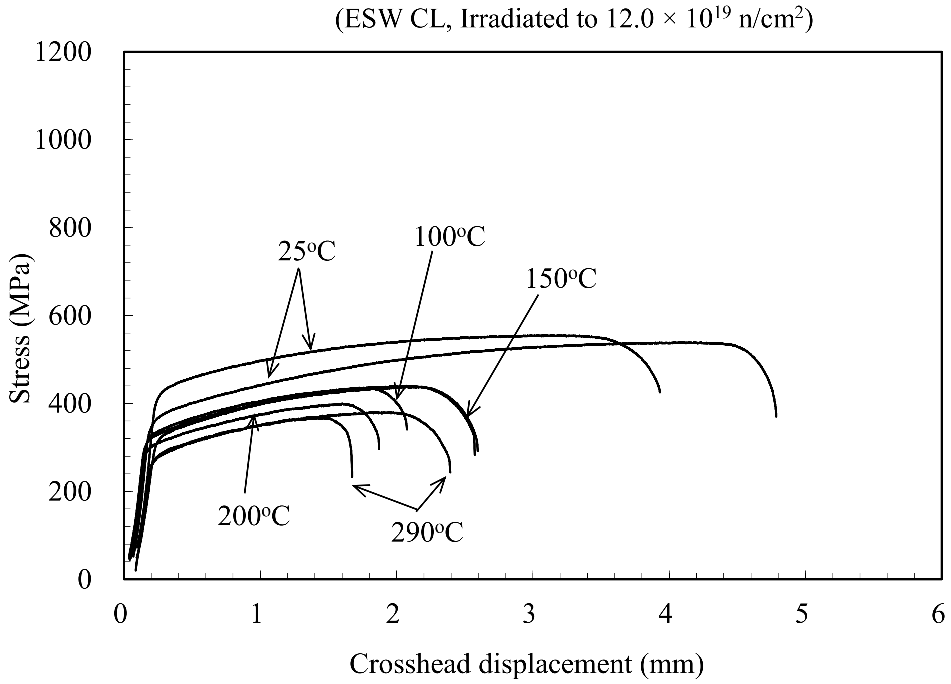
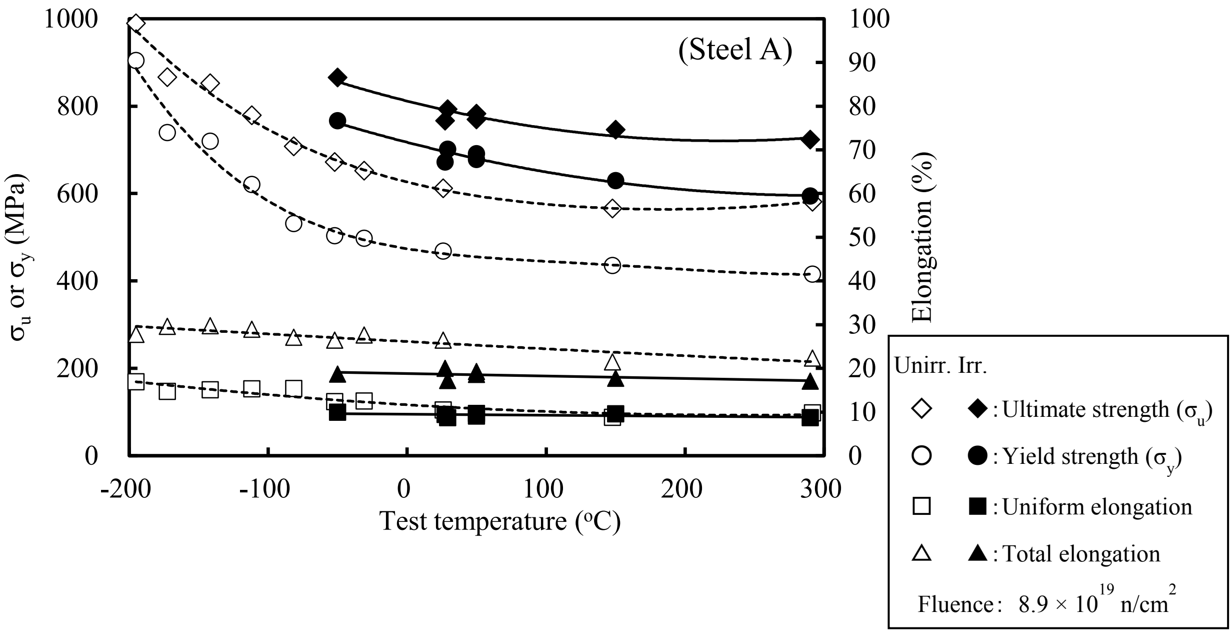


Fig.3.2-1 Stress-crosshead displacement curves (3/3)



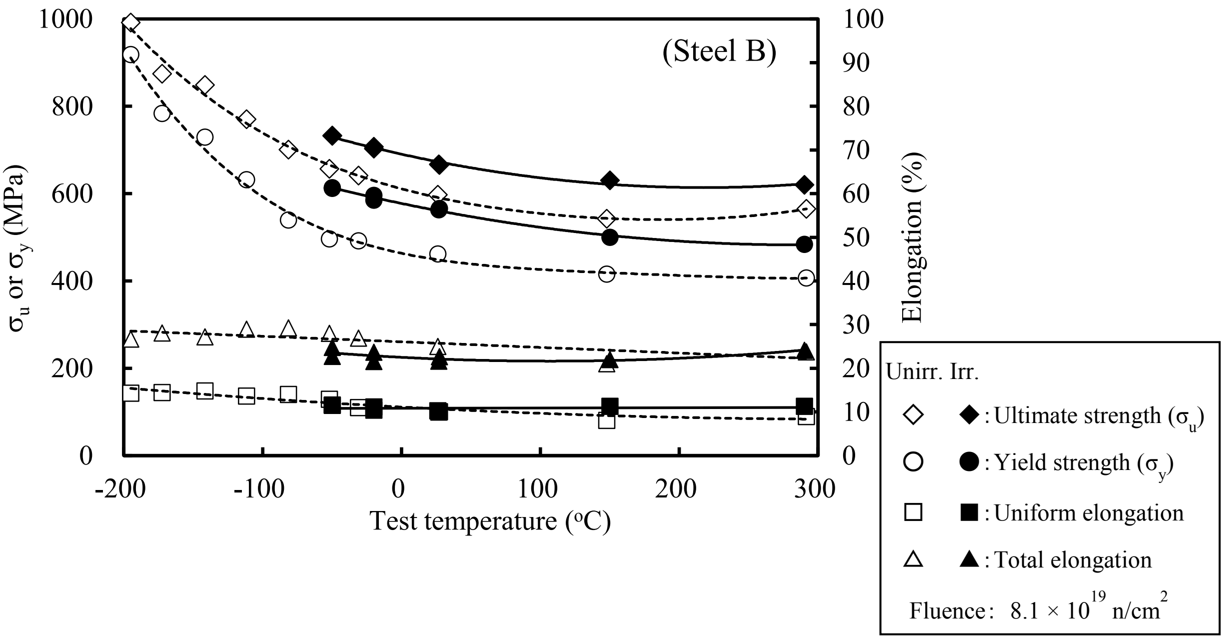
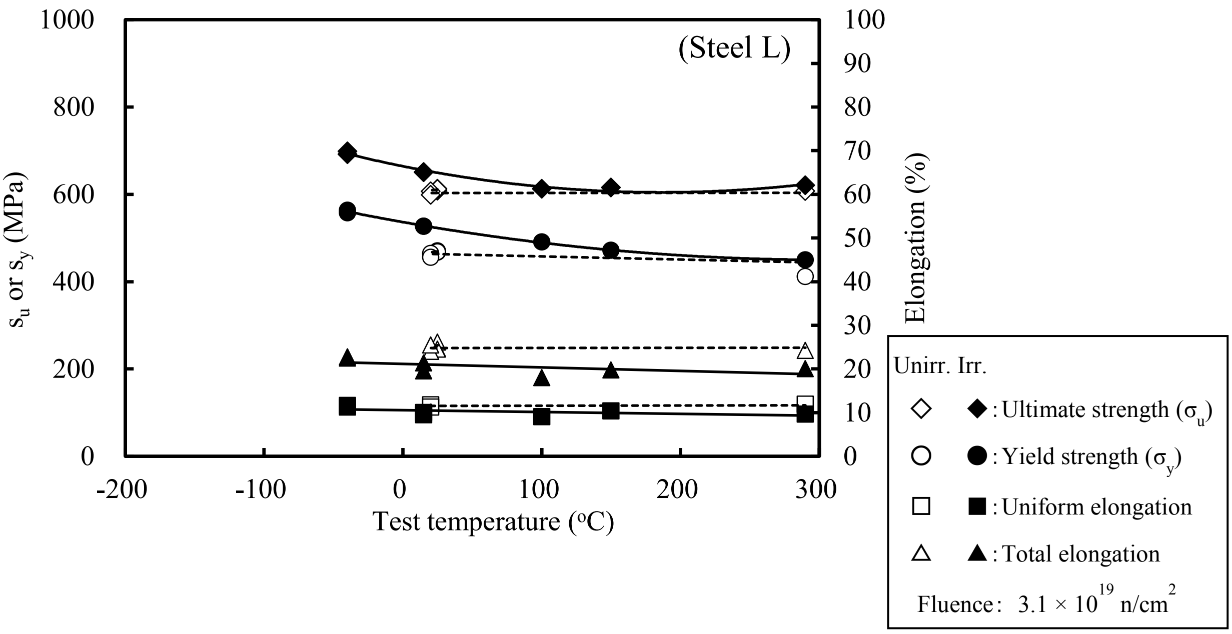


Fig. 3.2-2 Temperature dependence of tensile properties (1/4)



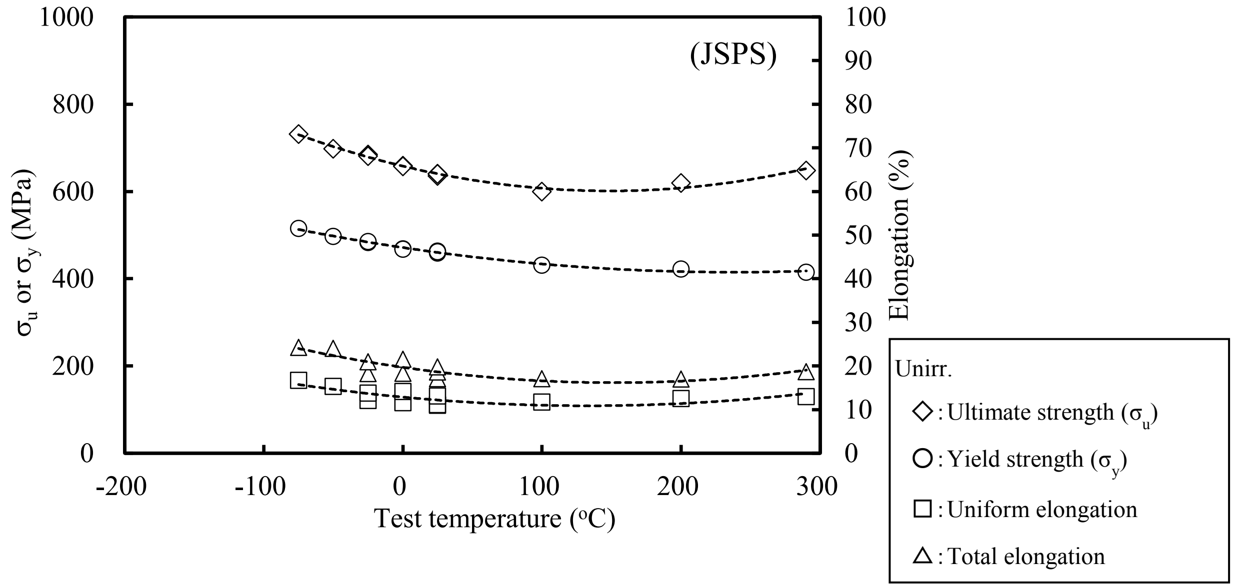


Fig. 3.2-2 Temperature dependence of tensile properties (2/4)

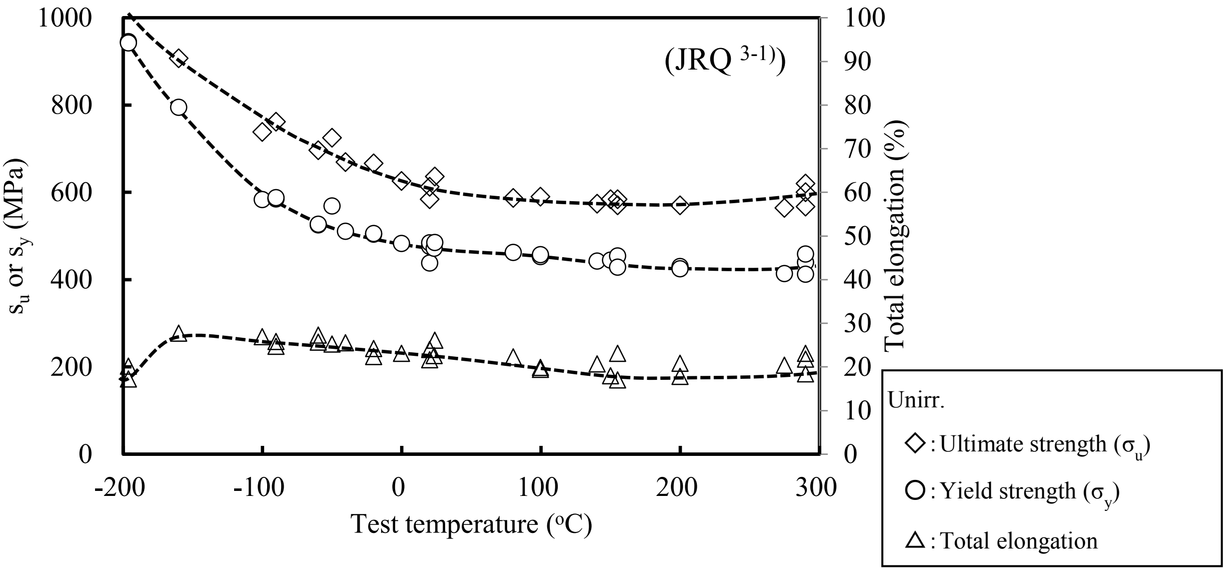
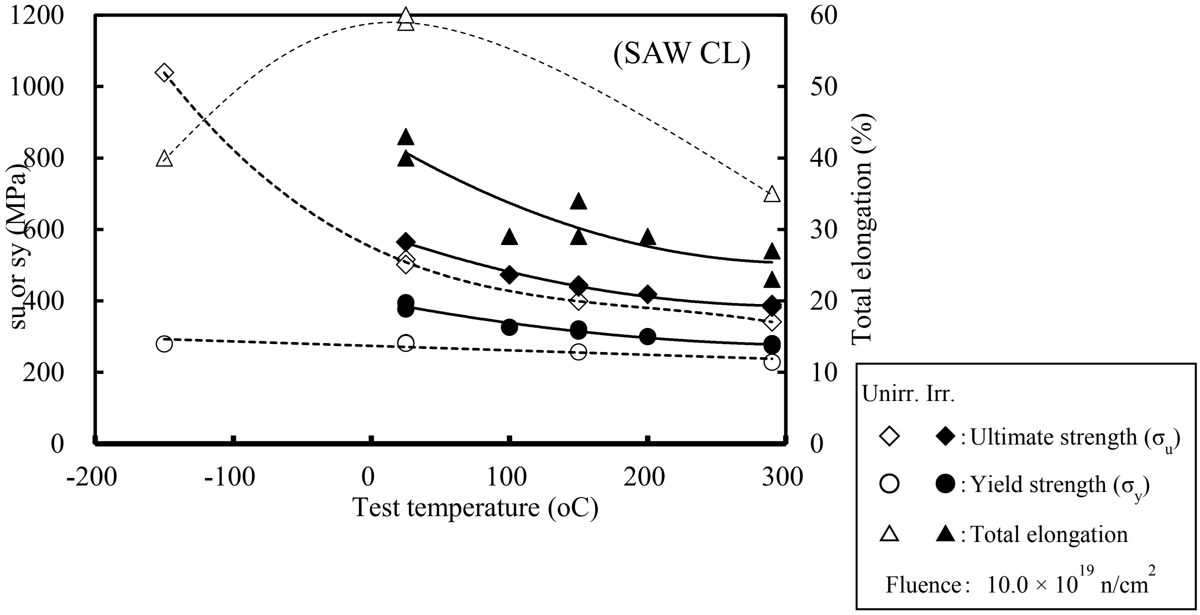


Fig. 3.2-2 Temperature dependence of tensile properties (3/4)



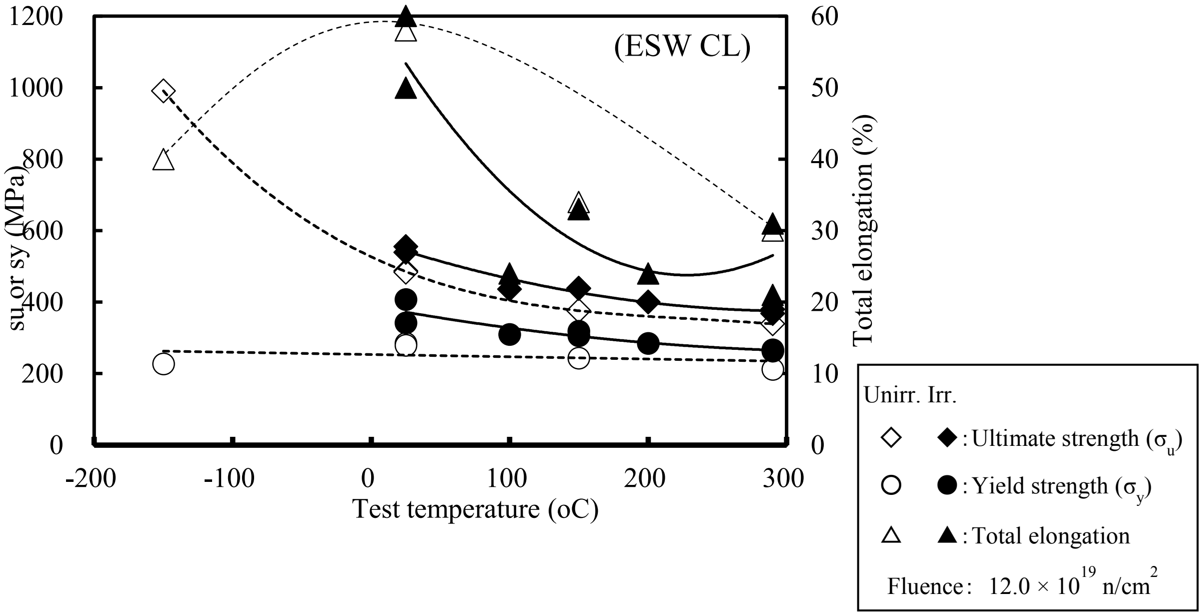


Fig. 3.2-2 Temperature dependence of tensile properties (4/4)

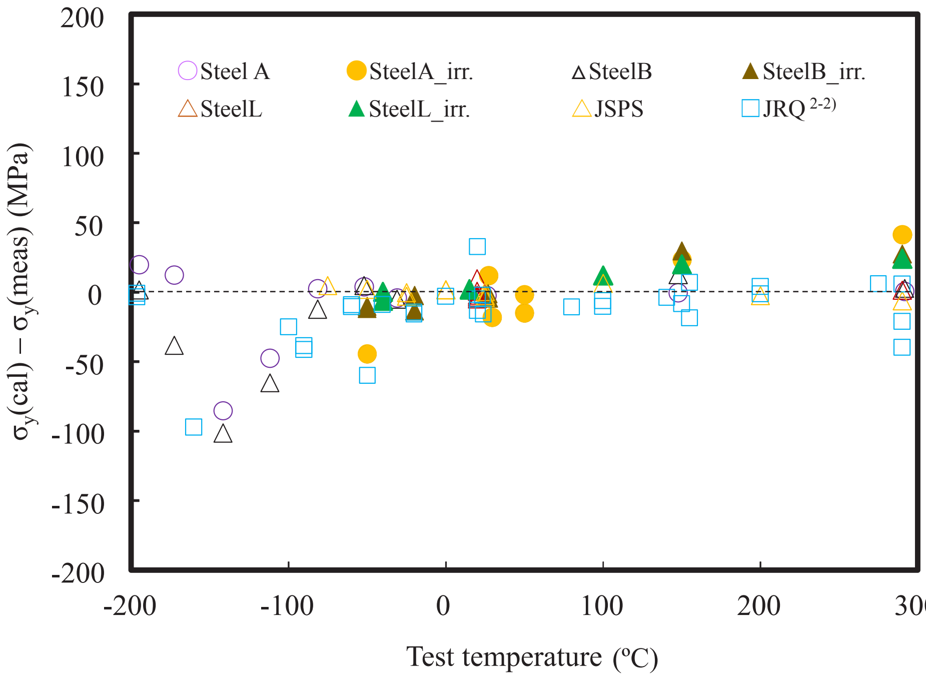


Fig. 3.2-3 The difference between the measured σ_y ($\sigma_{y(meas.)}$) and the calculated σ_y ($\sigma_{y(cal.)}$)

4. Charpy impact test

4.1 Test procedure

The Charpy impact test was performed using the 300-J Charpy impact testing machine with an International Organization for Standardization (ISO)-type hammer tup in the temperature range of -130 °C to 290 °C. The hammer speed at impact was ~5 m/s. The main specifications of the Charpy impact testing machine and schematic image of the test specimen are summarized and shown, respectively, in Table 4.1-1 and Fig. 4.1-1. All Charpy V-notch specimens were machined along the T-L orientation from the 1/4 thickness position of the steel plate.

The specimens were set in a temperature control bath for 15 min before testing. The media in the bath were alcohol for the low-temperature test and silicon oil for the high-temperature one. An automated specimen transfer system was used to maintain identical testing conditions for all specimens and to minimize the change in specimen temperature during transfer. The average time to impact of the specimens after removal from the temperature control bath was ~3.5 s.

4.2 Results

Charpy impact tests were conducted using all unirradiated materials, and the irradiated materials except JSPS. Charpy transition curves obtained in this study are shown in Fig. 4.2-1. As it can be seen in the figure, the materials exhibit ductile-brittle transition behavior with decreasing temperature because of the dominance of δ-ferrite phase. With neutron irradiation, a decrease in the upper-shelf energy (USE) and an increase in the Charpy 41 J temperature (T_{41J}) were observed. The results of the Charpy impact test are summarized in Table B of Appendix.

Table 4.1-1 Main specifications of 300J-Charpy impact testing machine

Hammer mass (kg)	26.6
Hammer edge	r =2mm (ISO type)
Centroid distance from rotation axis (m)	0.634
Gravitational acceleration (m/s^2)	9.8
Swing-up angle (degree)	144.5
Center of impact from rotation axis (m)	0.750
Capacity (J)	300
Blowing speed (m/s)	5.17
Resolution of impact force	12 bit
Sampling frequency	1 MHz

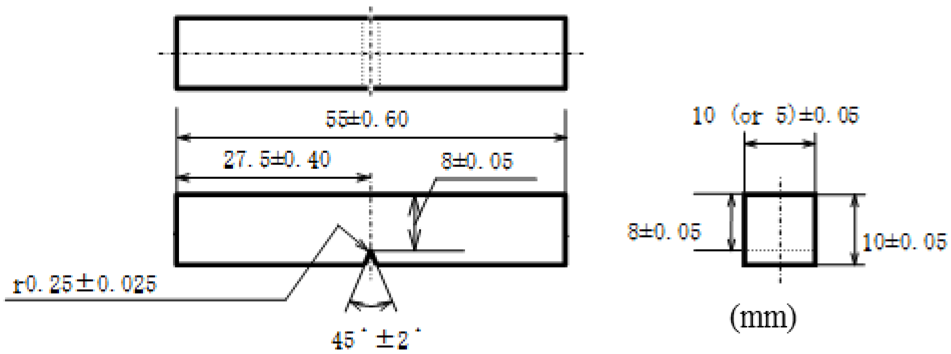
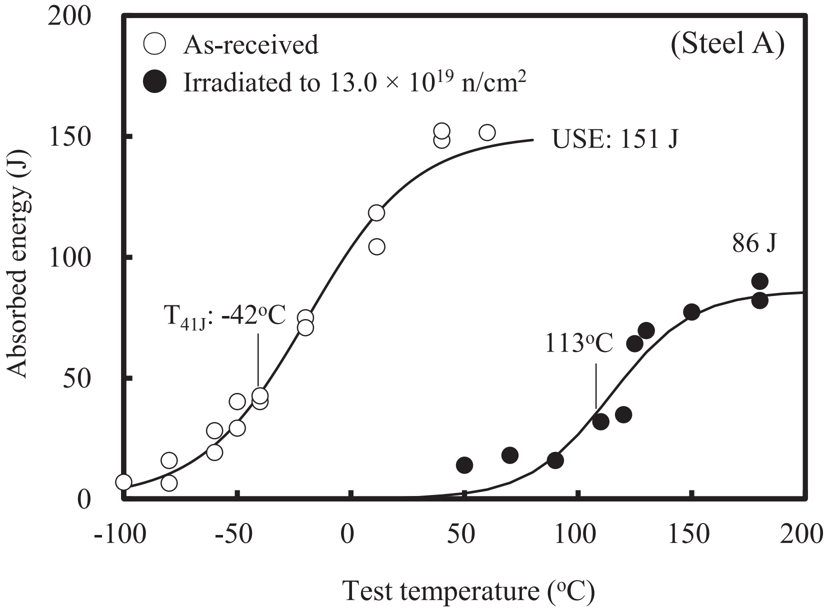


Fig. 4.1-1 Schematic image of Charpy impact test specimen



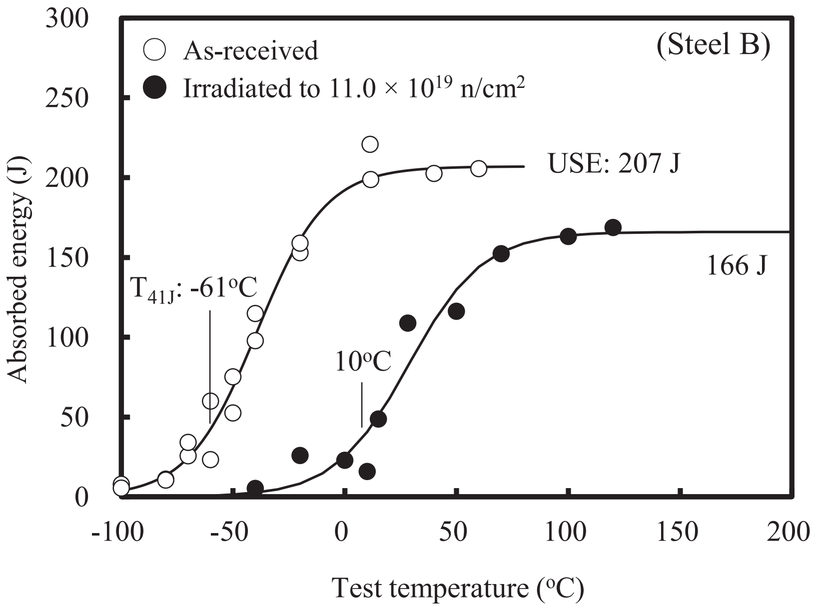
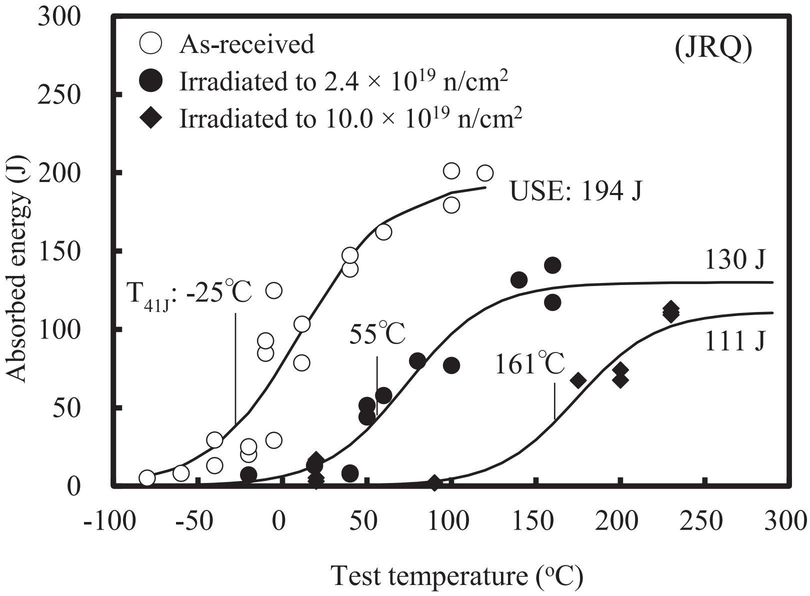


Fig. 4.2-1 Charpy transition curves (1/4)



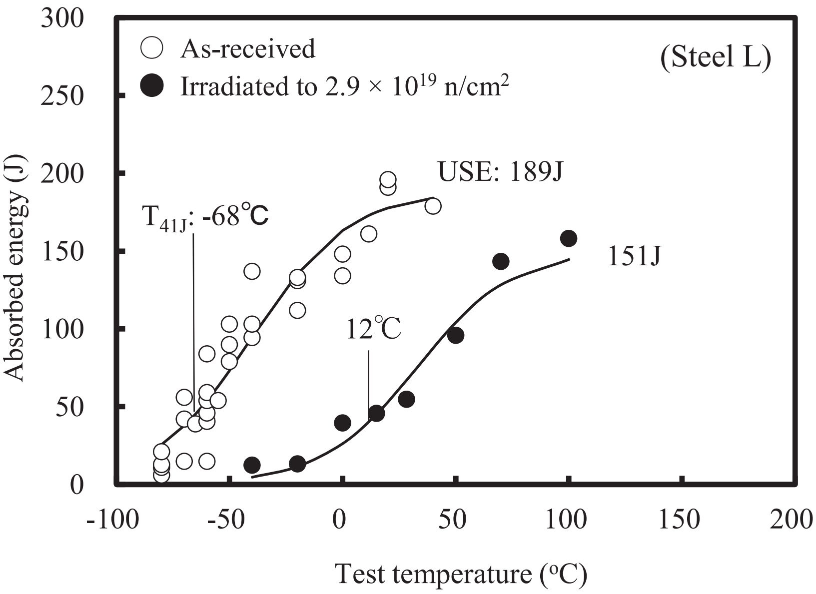


Fig. 4.2-1 Charpy transition curves (2/4)

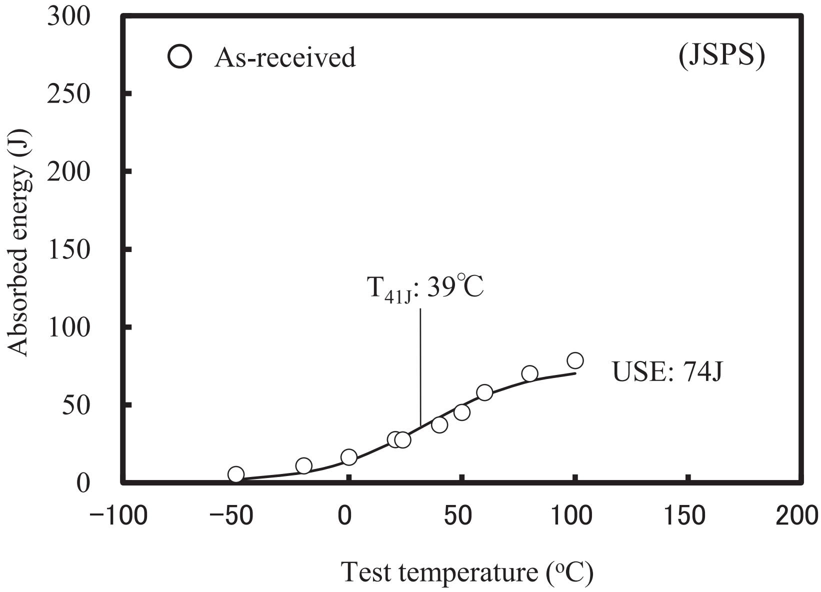
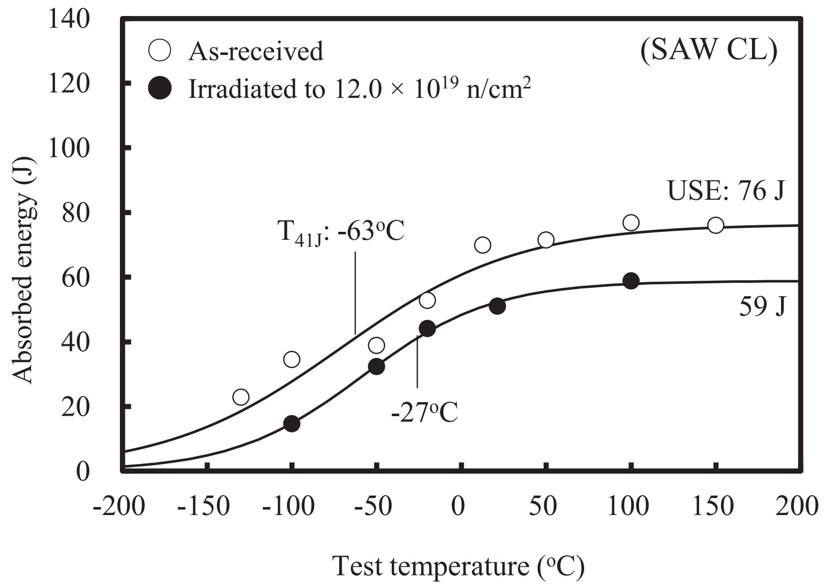


Fig. 4.2-1 Charpy transition curves (3/4)



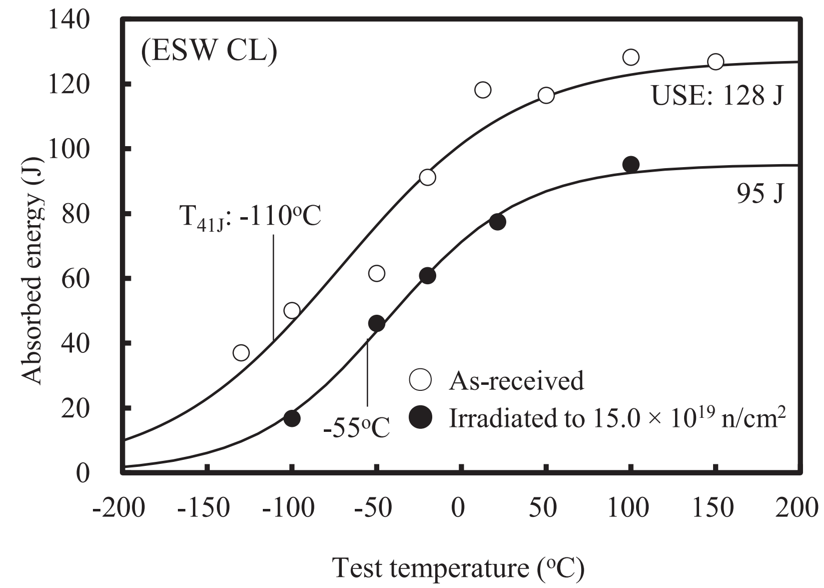


Fig. 4.2-1 Charpy transition curves (4/4)

5. Drop-weight test

5.1 Test procedure

The drop-weight test was performed using drop-weight tester in accordance with the ASTM standerd for conducting drop-weight test to determine nil-ductility transition temperature of ferritic steels (ASTM E 208). P-3-type drop-weight test specimens shown in Fig. 5.1-1 with a single-pass crackstarter weld bead were used in this test. The nil-ductility transition temperature (T_{NDT}) is defined in ASTM E 208 to be the highest temperature at which a specimen breaks, provided two tests at a temperature 5°C higher show no-break performance.

5.2 Results

Drop-weight tests were conducted using unirradiated Steels A and B. The series of specimens were taken in the T direction from the 1/4 thickness position of the steel plate. The results of the drop-weight tests and the obtained T_{NDT} are shown in Table 5.2-1.

Table 5.2-1 Drop-weight test data

Temperature (°C) / Material ID	-55	-50	-45	-40	-35	-30	-25	T_{NDT}* (°C)
Steel A				Break	Break	No Break No Break	No Break No Break	-35
Steel B	Break		Break	No Break No Break				-45

* As a result of the Charpy impact test at T_{NDT} + 33 °C, all three specimens absorbed energy of 68 J or more and underwent lateral expansion of 0.9 mm or more. That is, T_{NDT} can be considered the reference temperature for nil-ductility transition (RT_{NDT}).

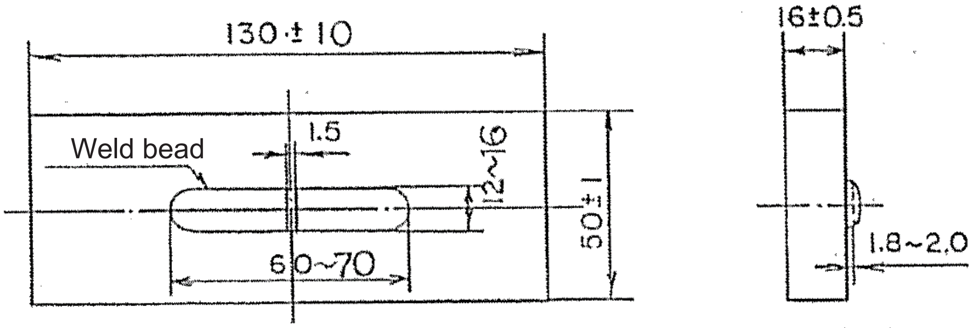


Fig. 5.1-1 Schematic image of drop-weight test specimen

6. Fracture toughness test

6.1 Master Curve method

Changes in the fracture toughness of RPV steels were evaluated from the initial fracture toughness and shifts in the Charpy energy transition curve due to neutron irradiation. To evaluate the structural integrity of RPVs, a lower-bound curve that enveloped the fracture toughness data was used. However, the lower-bound curve depended on the amount of data and scatter.

The MC method[1-1,1-2] is expected to be useful for direct evaluation of fracture toughness. This method allows for theoretical expression of the confidence limit considering the inherent statistical characteristics of fracture toughness. In the MC method, the relationship between temperature and median fracture toughness ($K_{Jc(med)}$) of a 1-inch-thick specimen is given as follows:

$$K_{Jc(med)} = 30 + 70\exp[0.019(T - T_o)],\ \mathrm{MPa}\sqrt{\mathrm{m}}, \qquad (6\text{-}1)$$

where

T: temperature (°C),

T_o: reference temperature (°C).

T_o is defined as the temperature at 100 MPa√m and is determined by at least six fracture toughness data points.

In the MC method, the fracture toughness value obtained from a small-sized specimen is adjusted to K_{Jc} value equivalent to a 1-inch-thick specimen ($K_{Jc(1Teq)}$) by the following equation:

$$K_{Jc(1Teq)} = K_{min} + (K_{Jc\_x} - K_{min})(B_x / B_{1T})^{1/4}, \qquad (6\text{-}2)$$

where

K_{Jc_x}: K_{Jc} for specimens of thickness B_x,

K_{min}: 20 MPa√m,

B_x: Thickness of specimen,

B_{1T} : Thickness of 1 inch thick specimen (=25.4mm).

Owing to the limited number of surveillance fracture toughness specimens in the surveillance capsule of Japanese early nuclear power plants, it was difficult to obtain sufficient data using the MC method in conjunction with the surveillance program for RPV steels. Therefore, many efforts have been made to create 4-mm-thick miniature compact tension (Mini-C (T)) specimens from broken surveillance Charpy specimens.

6.2 Test procedure

The fracture toughness tests using Mini-C (T), pre-cracked Charpy-V (PCCv), 0.4T-C (T), 1T-C (T) and 4T-C (T) specimens were performed using a 100 kN mechanical-servo type testing machine. Specimen preparation and testing were conducted according to the ASTM standard [1-1),6.2-1)] and according to studies in the literature [6.2-2)]. Due to the difference in the test period, fracture toughness tests using Mini-C (T) specimens and other (PCCv, 0.4T-C(T) , 1T-C(T)) specimens were conducted according to ASTM E 1921-12 and ASTM E 1921-97, Respectively. Schematic images of the test specimens are shown in Fig. 6.2-1. The specimens were machined along the T-L orientation from the 1/4 thickness position of the steel plate. All specimens were side-grooved by 10% on each side after fatigue precracking. For the fatigue precracking, the maximum applied stress intensity factor was 20 MPa√m in the first precracking step and 15 MPa√m in the final step. A calibrated load cell and a clip gauge were used for measuring the applied load and load point displacement, respectively.

Before testing, the temperature of the test specimen and the fixture inside the testing chamber were maintained at the target temperature for 20 min. Cold nitrogen gas was injected into the chamber for low-temperature testing. The temperature distribution around the specimen was measured using calibrated thermocouples. One thermocouple was attached to the upper fixture. The other thermocouples were buried in the dummy specimens and located close to the test specimen. The temperatures of all thermocouples and, hence, that of the test specimen were then controlled to the target temperature within a variation of 1°C during testing.

6.3 Results

Fracture toughness tests were conducted using unirradiated materials (Steel A, Steel B, JRQ, Steel L and JSPS) and irradiated materials (Steel A, Steel B and JRQ). The K_{Jc} and $K_{Jc(1Teq)}$ values obtained in the test are summarized in Table C of Appendix. The full cleavage fracture surface of all tested specimens was observed. Invalid K_{Jc} data exceeding $K_{Jc(limit)}$ were omitted based on the $K_{Jc(limit)}$ value according to ASTM E1921. The $K_{Jc(1Teq)}$ values are plotted against the test temperature in Fig. 6.3-1 along with the MC. The T_o values were determined mainly by using the multi-temperature method according to ASTM E1921, and results are summarized in Table 6.3-1. The T_o values of JRQ are within the range of scatter of the IAEA round-robin test results[6.3-1)].

The T_o values of all the specimens of the materials are shown in Fig. 6.3-2. The error bars in this figure represent the standard deviation (σ) in the estimation of T_o, which incorporates sample size and experimental uncertainties and is given by following equation;

$$\sigma = (\beta^2/r + (\sigma_{exp})^2)^{0.5}, \qquad (6\text{-}3)$$

where

β: the sample size uncertainty factor determined based on 1T-equivalent $K_{Jc(med)}$, r: the total number of valid K_{Jc} data points,

σ_{exp} : the contribution of experimental uncertainties.

The T_o values determined using the Mini-C (T) specimens as well as the 0.4T-C (T) specimens showed good agreement overall with those determined using the 1T-C (T) specimens. In case of the PCCv specimens, all T_o values were lower than those determined using the 1T-C (T) specimens. In this regard, a study [6.3-1] reported that the T_o of bending-type specimens is approximately 8 °C lower than that of the CT-type specimens, probably because of the difference in constraint near the crack tip.

With regard to evaluation of the fracture toughness of RPV steels based on the MC method, the 5% lower-bound of the MC was adopted as new fracture toughness curve for pressurerized thermal shock (PTS) evaluation in Japanese electric association codes[6.3-2] revised recent year. Yoshimoto et al. [6.3-3] proposed T_{41J}-based lower-bound curves of $K_{Jc(1Teq)}$ expressed by Eq. (6-4).

$$K_{Jc(0.xx)} = 20 + [\ln\{1/(1 - 0.xx)\}]^{1/4} \{11 + 77\exp[0.019(T - (T_{41J} + \Delta T_t))]\}, \qquad (6\text{-}4)$$

where

0.xx: cumulative probability level of xx%,

T_{41J}: Charpy 41J transition temperature,

ΔT_t: -15°C for plate and 14°C for weld materials.

The fracture toughness data of all the specimens normalized by $T_{41J} + \Delta T_t$ are shown in Fig. 6.3-3. The data of irradiated materials obtained using the PCCv specimens are plotted in the same figure as well. The solid line in the figure is the new fracture toughness curve for PTS evaluation, i.e. the 5% (xx = 05) lower bound of the MC. Most of the data, including those of the 4T-C (T) and the irradiated PCCv specimens, were enveloped by the proposed lower bound with a ratio of approximately 98%.

Table 6.3-1 Reference temperature (T_o) data

Material ID	Fluence (10^{19} n /cm^2)	Specimen type	Test temperature range (°C)	Loading rate dK/dt (MPa√m/s)	No. of total data		No. of valid data		T_o (°C)*1		Standard deviation of estimate of T_o (°C)	
Steel A	0	Mini-C (T)	-100	0.1	9	29	9	27	-72	-67	7.4	5.4
			-90 to -100	0.5	10		8		-70		7.5	
			-100	1.8	10		10		-58		7.5	
		PCCv	-80 to -100	1.0	42		34		-76		4.9	
		1T-C (T)	-30 to -80	0.8	32		32		-66		5.1	
	13	PCCv	50	1.0	8		8		73		7.8	
Steel B	0	Mini-C (T)	-120	0.1	10	30	10	29	-86	-91	7.2	5.3
			-120	0.5	10		9		-102		7.2	
			-120	1.8	10		10		-78		7.5	
		PCCv	-110 to -130	1.0	32		29		-109		5.2	
		1T-C (T)	-60 to -110	0.8	32		32		-97		5.1	
	11	PCCv	-50	1.0	7		7		-24		8.2	
JRQ	0	Mini-C (T)	-100 to -110	0.5	12		11		-80		6.9	
		PCCv	-80	1.0	16		16		-65		6.2	
		0.4T-C (T)	-50 to -80	0.5	15		15		-65		6.1	
		1T-C (T)	-50 to -80	0.8	9		9		-65		7.2	
	11	PCCv	100	1.0	8		8		134		7.8	
Steel L	0	PCCv	-100 to -130	1.0	22		15		-114		6.1	
		1T-C (T)	-100	0.8	6		6		-117		8.4	
	2.9	PCCv	-40	1.0	12		12		-24		6.7	
JSPS	0	PCCv	-25	1.0	8		8		2		7.8	

*1 Fracture toughness tests using Mini-C (T) specimens and other (PCCv, 0.4T-C(T) , 1T-C(T)) specimens were conducted according to ASTM E 1921-12 and ASTM E 1921-97, Respectively.

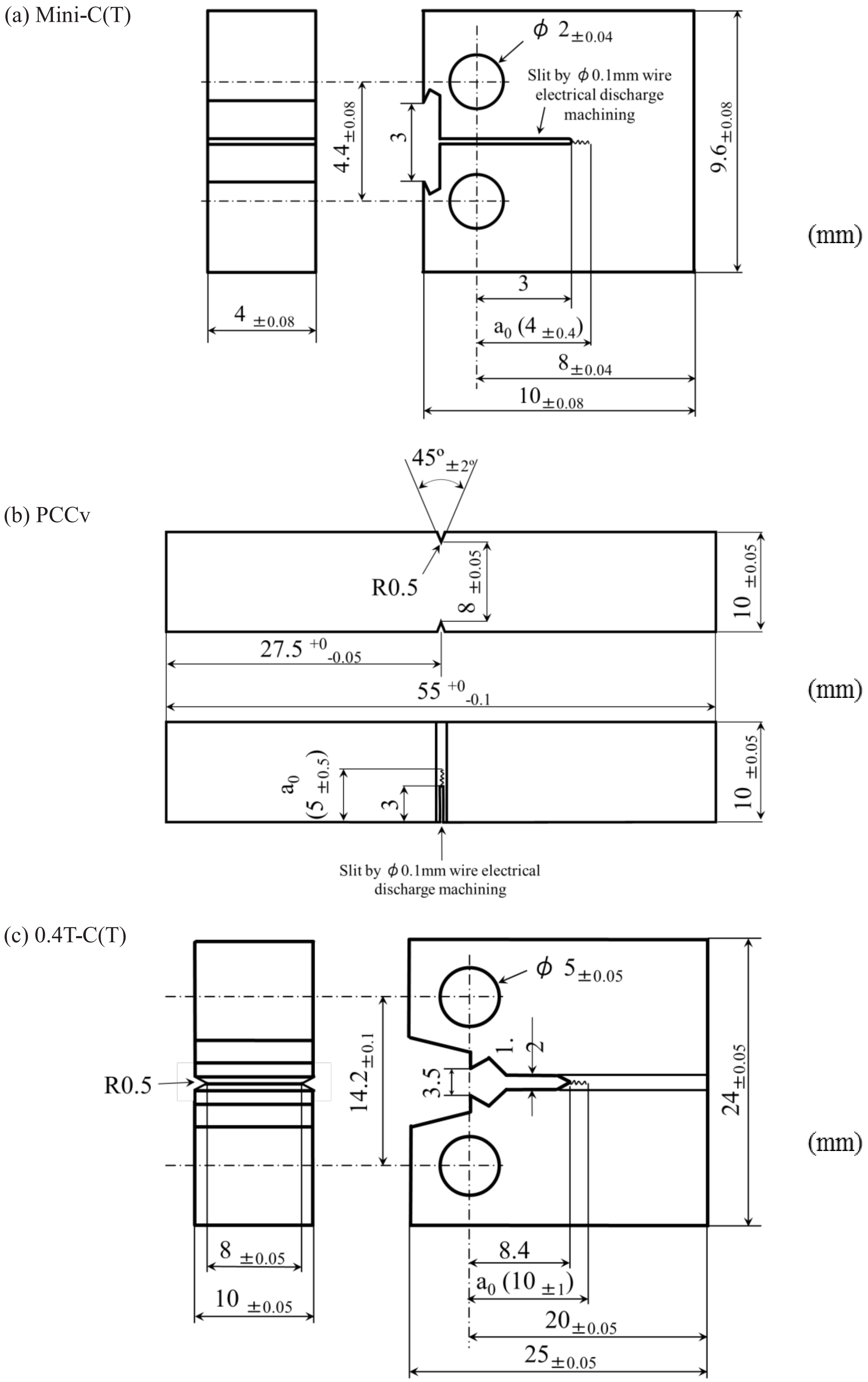
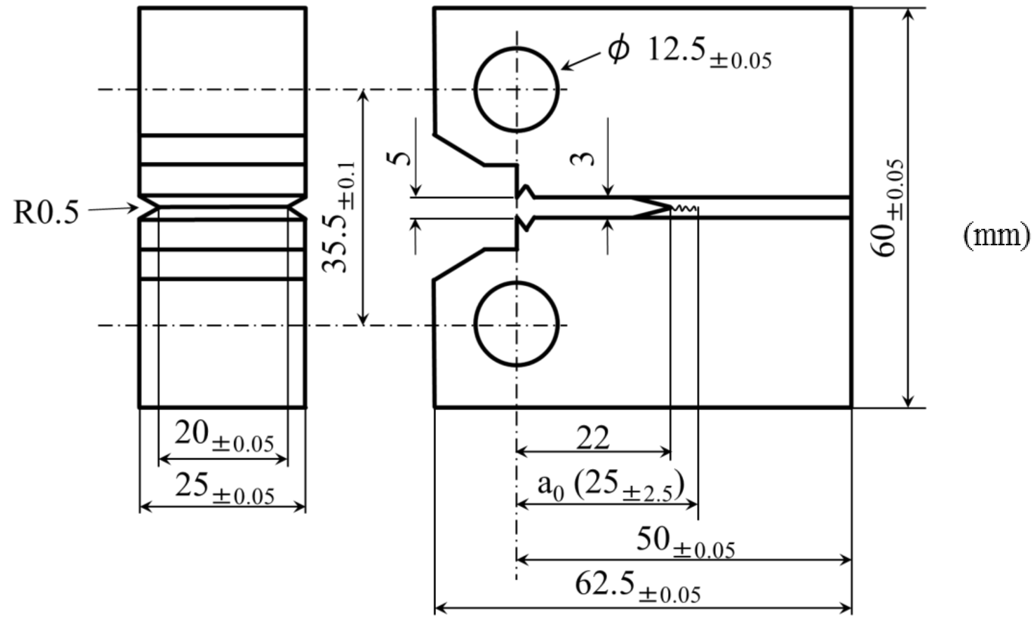


Fig. 6.2-1 Schematic images of fracture toughness test specimens (1/2)

(d) 1T-C(T)



(e) 4T-C(T)

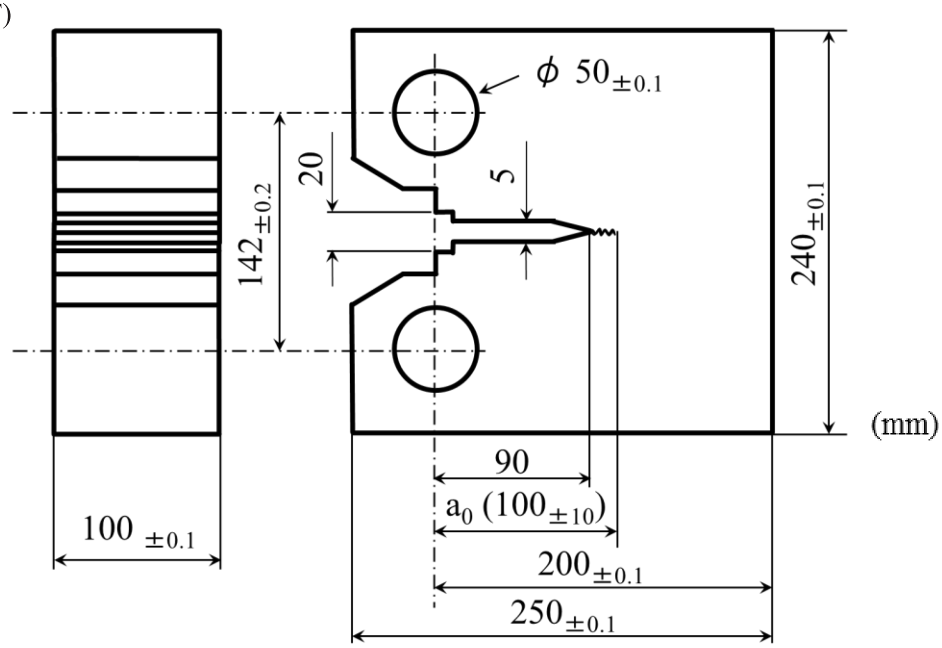


Fig. 6.2-1 Schematic images of fracture toughness test specimens (2/2)

<Material: Steel A>

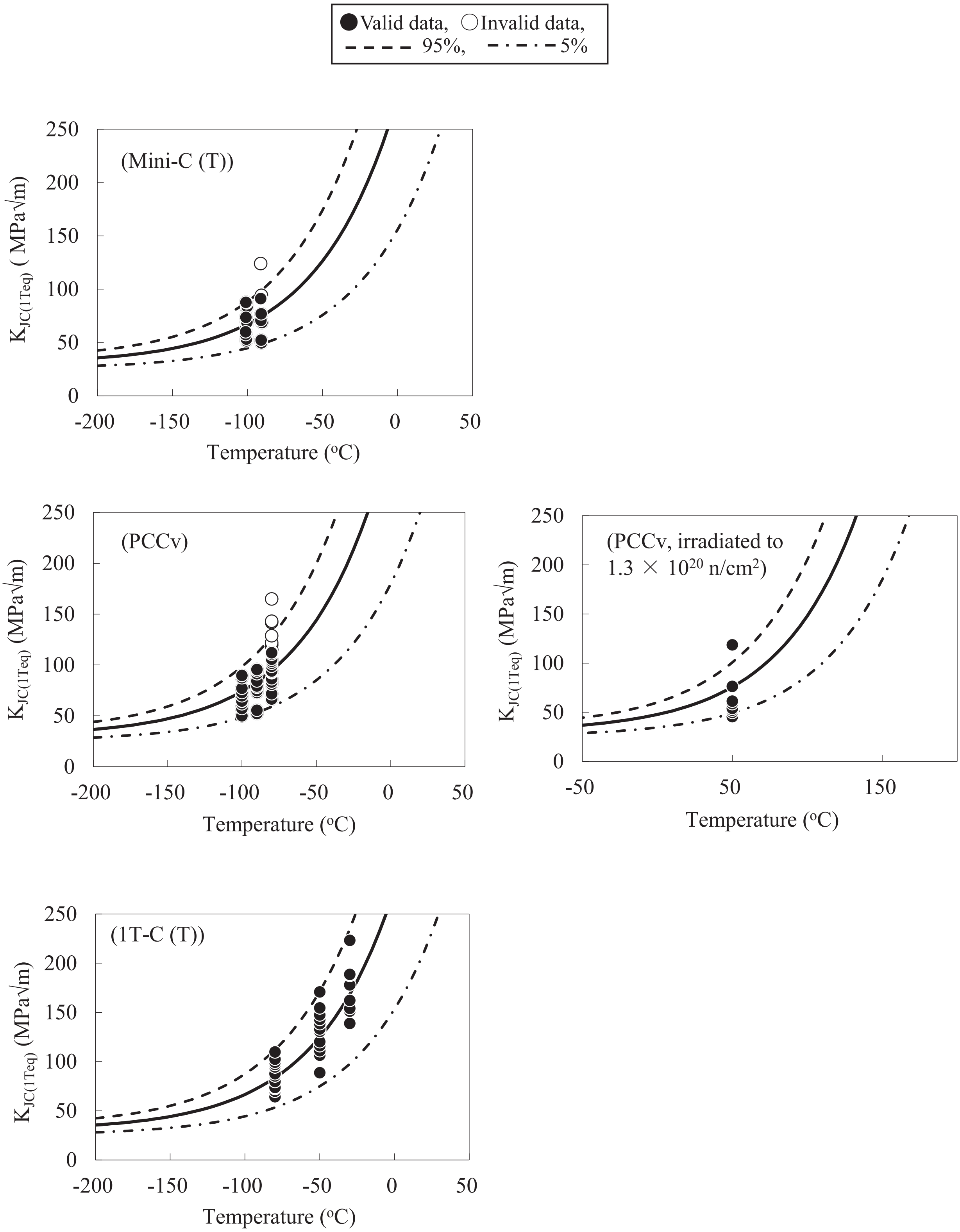


Fig. 6.3-1 1T-equivalent fracture toughness $K_{Jc(1Teq)}$ and master curve (1/4)

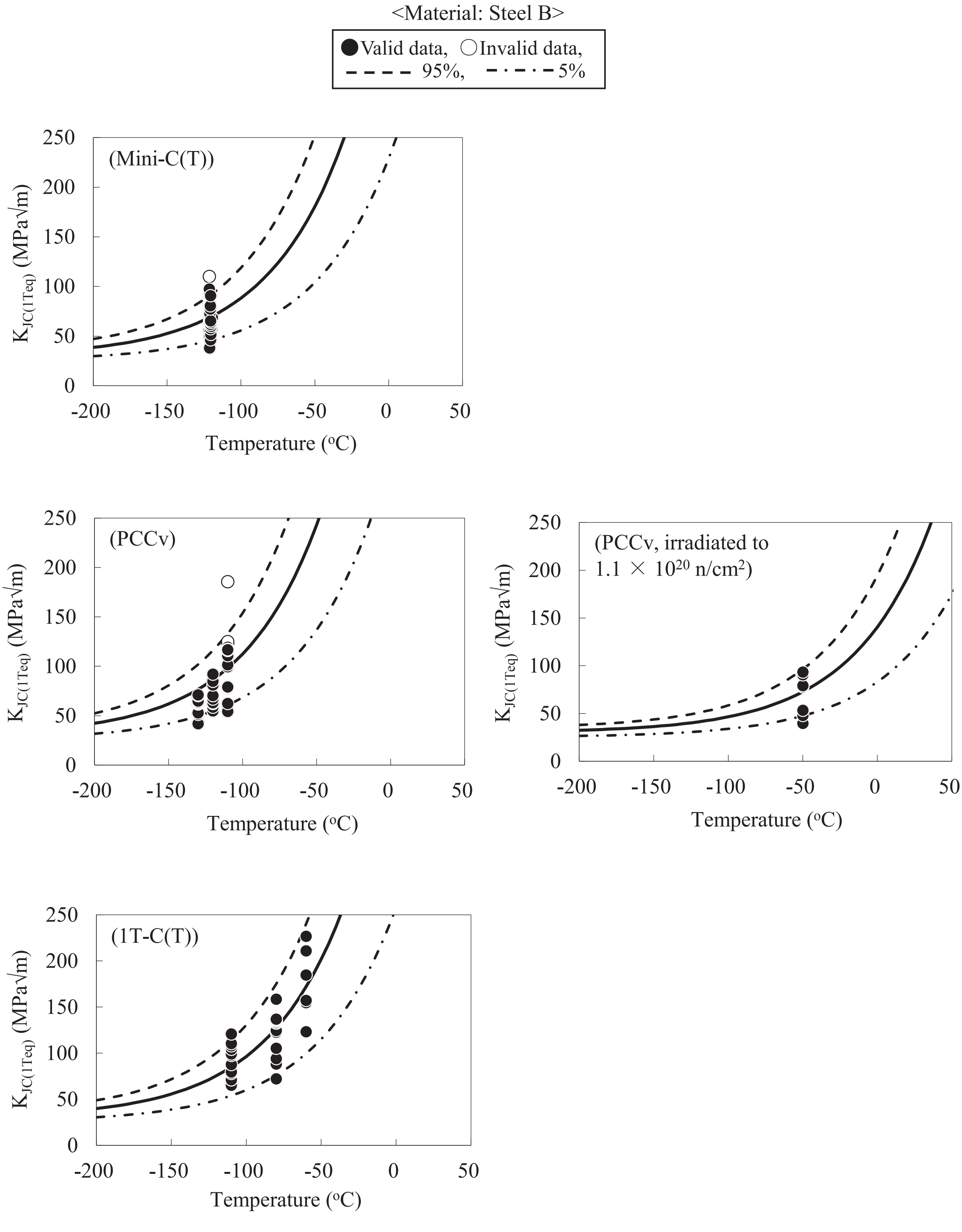


Fig. 6.3-1 1T-equivalent fracture toughness $K_{Jc(1Teq)}$ and master curve (2/4)

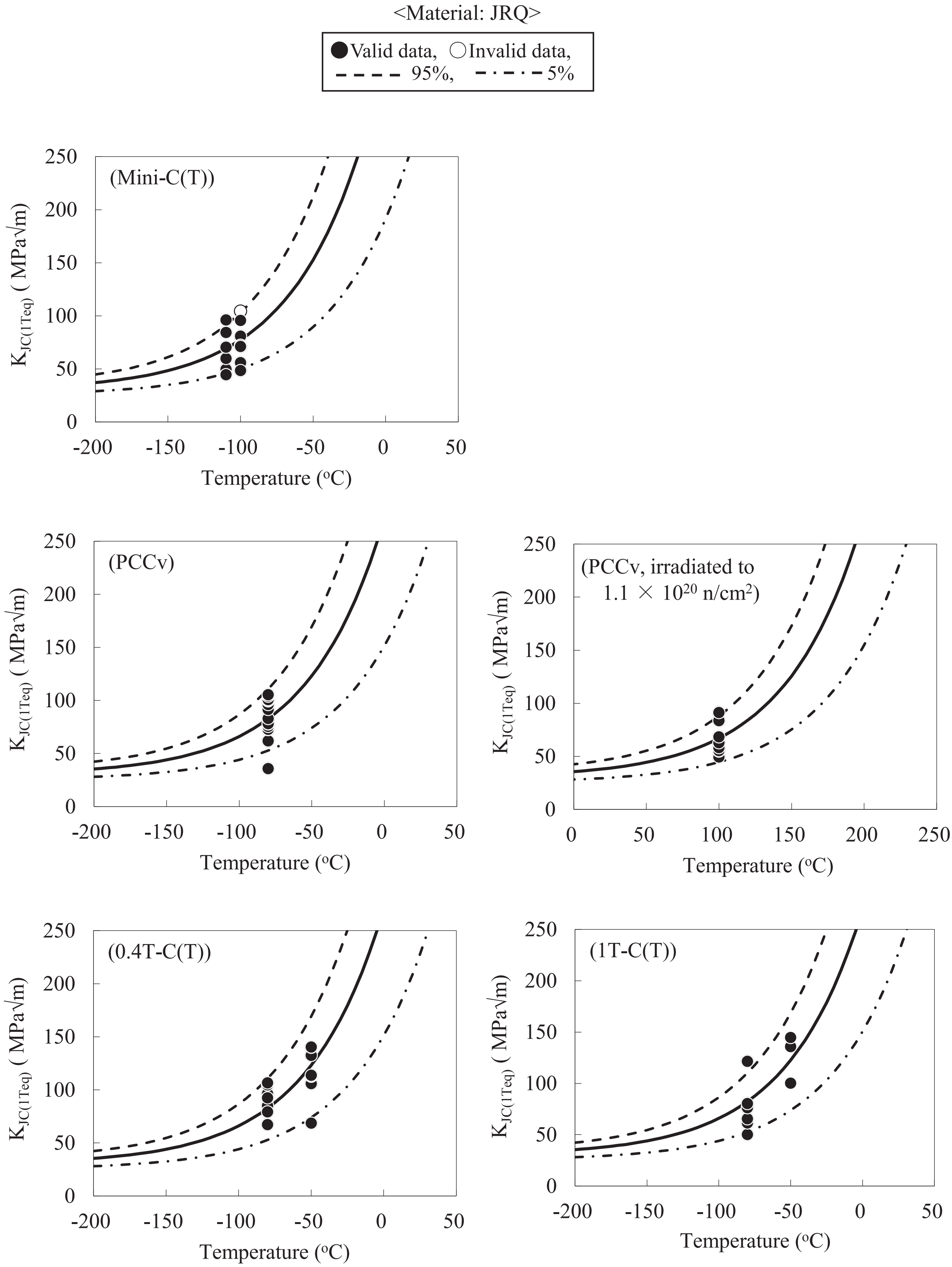
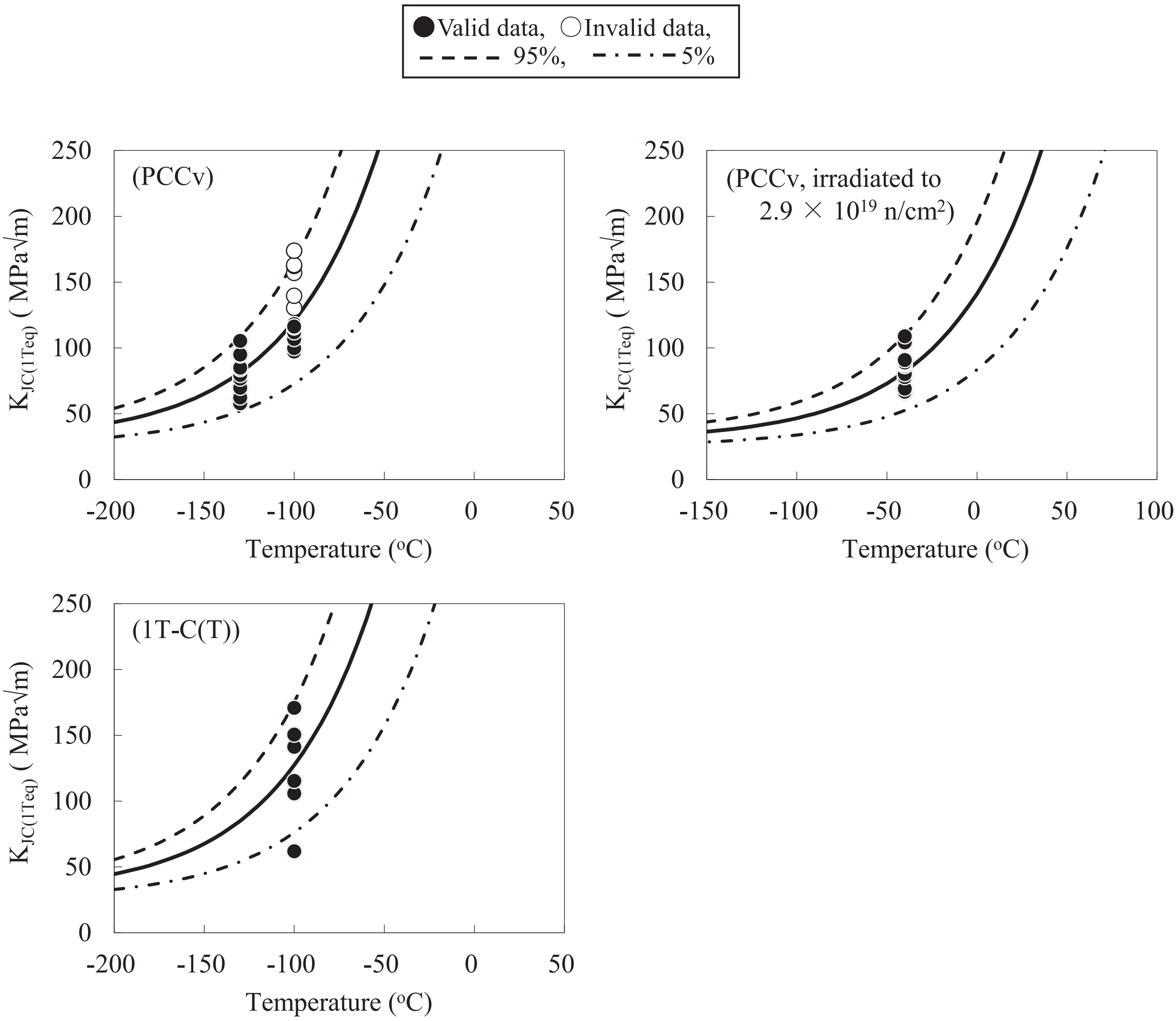


Fig. 6.3-1 1T-equivalent fracture toughness $K_{Jc(1Teq)}$ and master curve (3/4)

<Material: Steel L>



<Material: JSPS>

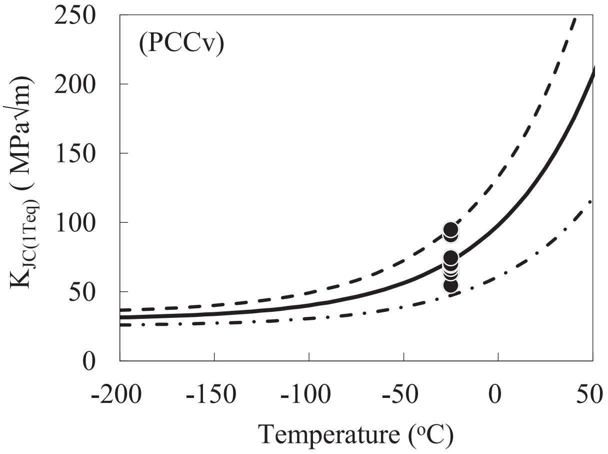


Fig. 6.3-1 1T-equivalent fracture toughness $K_{Jc(1Teq)}$ and master curve (4/4)

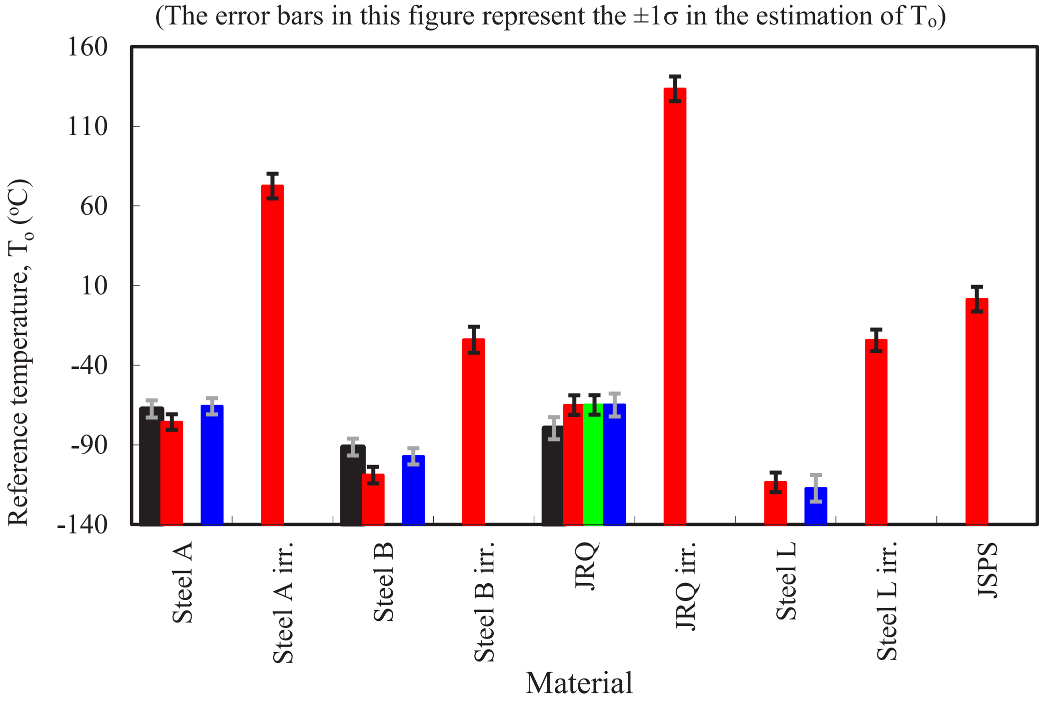


Fig. 6.3-2　Reference temperatures of all specimens for each material

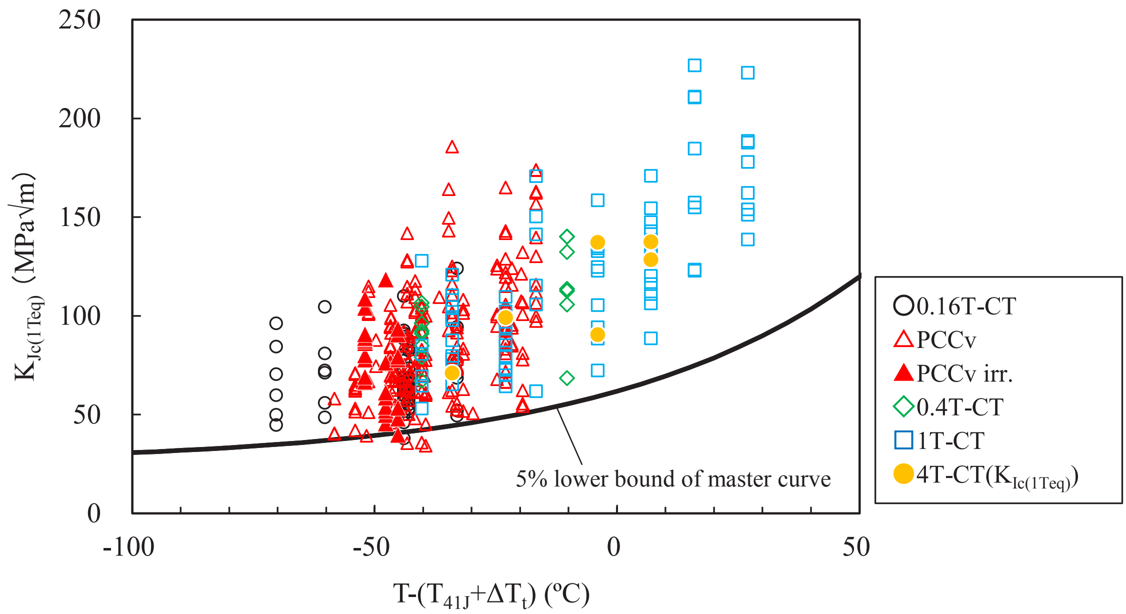


Fig. 6.3-3　1T-equivalent fracture toughness, $K_{Jc(1Teq)}$ normalized by T_{41J} obtained by Charpy impact test with 5% lower bound of master curve

7. Summary

Many tests including irradiation tests related to structural integlity assessment of RPV have been performed. Material tests such as tensile, drop-weight, Charpy impact, and fracture toughness tests of RPV steels were carried out using five types of ASTM A533B Class1 steels with different impurity contents and fracture toughness levels, and the test results arewere summarized in this research report. Especially in the fracture toughness test, a large number of tests using specimens with different sizes and shapes were conducted, and the applicability of the master curve method which introduced in Japanese electric association codes in recent years was also confirmed.

The data summarized in this research report will be useful to the structural integrity assessments of RPVs and evaluation of irradiation embrittlement of RPV steels.

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Appendix: Test data lists

Test data lists consist of the following Tables.

- Table A Tensile test data
- Table B Charpy impact test data
- Table C Fracture toughness test data

Table A Tensile test data (1/3)

(UE: Uniform elongation; TE: Total elongation; RA: Reduction of area)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	σ_y (MPa)	σ_u (MPa)	UE (%)	TE (%)	RA (%)
Steel A	0	-195	905	990	17.0	27.8	51.6
		-173	739	866	14.7	29.6	58.9
		-142	720	853	15.1	29.8	59.4
		-112	621	779	15.3	29.0	64.7
		-82	532	708	15.4	27.1	68.2
		-52	504	672	12.4	26.4	67.9
		-31	498	653	12.5	27.7	68.6
		26	469	612	10.5	26.4	70.6
		148	435	566	8.8	21.5	69.7
		292	416	582	9.9	22.4	67.2
	8.9 @290ºC	-50	766	866	10	18.7	
		27	672	767	9.5	20.0	
		29	701	793	8.8	17.2	
		50	678	770	9.7	19.3	
		50	691	783	9.1	18.7	
		150	630	746	9.6	17.8	
		290	594	723	8.8	17.1	
Steel B	0	-195	918	991	14.3	26.7	55.0
		-173	784	874	14.5	28.1	65.2
		-142	729	849	14.8	27.2	64.1
		-112	632	770	13.6	28.9	70.6
		-82	539	700	14.0	29.2	71.8
		-52	496	656	12.9	28.0	74.1
		-31	492	641	11.0	26.9	72.6
		26	462	597	10.3	24.9	75.7
		148	416	542	8.0	21.0	73.7
		292	407	565	8.9	23.7	73.0
	8.1 @290ºC	-50	585	703	10.4	21.5	
		-50	612	733	11.6	24.8	
		-20	585	703	10.4	21.5	
		-20	596	707	11.1	23.6	
		27	562	667	10.0	21.6	

Table A Tensile test data (2/3)

(UE: Uniform elongation; TE: Total elongation; RA: Reduction of area)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	σ_y (MPa)	σ_u (MPa)	UE (%)	TE (%)	RA (%)
Steel B	8.1 @290ºC	27	565	666	10.0	22.6	
		150	500	630	11.3	22.0	
		290	484	620	11.3	24.1	
Steel L	0	25	471	613		24.7	73.5
		25	468	609		26.2	73.5
		25	469	612		24.6	72.2
		20	465	607	11.8	24.1	72.8
		20	456	599	11.3	25.5	74
		290	412	608	12	24.3	73.7
	3.1 @290ºC	-40	564	699	11.7	22.5	
		-40	558	692	11.3	22.8	
		15	527	651	9.59	19.59	
		15	527	651	10.05	21.41	
		100	491	613	9.14	18.05	
		150	472	616	10.41	19.82	
		290	450	621	9.73	20.09	
JSPS	0	-75	515	732	16.7	24.3	
		-50	497	698	15.3	24.1	
		-25	483	685	12.1	18.3	58.0
		-25	486	681	13.8	21.0	52.1
		0	468	659	11.6	18.3	61.9
		0	468	658	14.1	21.6	54.0
		25	459	636	11.0	17.1	61.3
		25	463	641	11.1	18.6	57.9
		25	462	640	13.1	19.8	57.8
		100	431	600	11.8	17.1	
		200	422	619	12.6	17.0	
		290	415	648	13.0	18.7	
SAW CL	0	-150	279	1039		40	
		25	283	516		59	
		25	281	501		60	
		150	257	399		34	

Table A Tensile test data (3/3)

(UE: Uniform elongation; TE: Total elongation; RA: Reduction of area)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	σ_y (MPa)	σ_u (MPa)	UE (%)	TE (%)	RA (%)
SAW CL	0	290	228	341		35	
	10.0 @290ºC	25	395	564		40	
		25	377	565		43	
		100	326	473		29	
		150	321	444		29	
		150	315	439		34	
		200	300	418		29	
		290	274	389		27	
		290	280	382		23	
ESW CL	0	-150	227	991		40	
		25	285	487		58	
		25	279	484		58	
		150	243	376		34	
		290	212	339		30	
	12.0 @290ºC	25	407	555		50	
		25	342	539		60	
		100	310	436		24	
		150	319	439		33	
		150	306	438		33	
		200	285	400		24	
		290	263	380		31	
		290	267	368		21	

Table B Charpy impact test data (1/6)

(T_{41J}: Charpy 41 J temperature, USE: Upper-shelf energy)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	Absorbed energy (J)	Shear fracture (%)	Lateral Expansion (mm)	T_{41J} (°C)	USE (J)
Steel A	0	-100	6.9	0	0.010	-42	151
		-80	15.9	0	0.067		
		-80	6.5	0	0.036		
		-60	19.2	5	0.129		
		-60	28.2	5	0.202		
		-50	29.3	5	0.284		
		-50	40.3	10	0.456		
		-40	40.3	10	0.715		
		-40	42.7	10	0.708		
		-20	74.9	25	1.233		
		-20	70.9	25	1.220		
		11	118.4	80	1.657		
		11	104.4	65	1.677		
		40	148.4	100	2.248		
		40	152.2	100	2.193		
		60	151.6	100	2.187		
	13 @290ºC	50	14.0	7	0.195	113	86
		70	18.1	11	0.494		
		90	16.0	22	0.419		
		110	32.0	24	0.584		
		120	34.8	37	0.656		
		125	64.2	71	1.213		
		130	69.7	82	1.426		
		150	77.3	82	1.445		
		180	82.1	100	1.468		
		180	90.1	100	1.711		
Steel B	0	-100	8.0	0	0.027	-61	207
		-100	5.6	0	0.016		
		-80	11.2	0	0.022		
		-80	10.6	0	0.040		
		-70	25.7	5	0.233		
		-70	34.2	5	0.224		

Table B　Charpy impact test data (2/6)
(T_{41J}: Charpy 41 J temperature, USE: Upper-shelf energy)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	Absorbed energy (J)	Shear fracture (%)	Lateral Expansion (mm)	T_{41J} (°C)	USE (J)
Steel B	0	-60	59.9	10	0.697	-61	207
		-60	23.4	5	0.152		
		-50	52.5	15	0.623		
		-50	75.2	20	0.985		
		-40	97.9	30	1.343		
		-40	114.9	40	1.778		
		-20	153.0	70	2.059		
		-20	159.0	75	2.165		
		11	220.9	100	2.625		
		12	198.8	100	2.421		
		40	202.5	100	2.437		
		60	205.6	100	2.568		
	11 @290ºC	-40	5.3	2	0.091	10	166
		-20	25.9	7	0.431		
		0	22.9	18	0.437		
		10	16.0	14	0.347		
		15	48.7	31	0.825		
		28	108.9	54	1.590		
		50	116.2	67	1.779		
		70	152.3	84	2.195		
		100	163.2	100	2.285		
		120	168.7	100	2.342		
JRQ	0	-80	5.2	0	0.023	-25	194
		-60	8.3	0	0.059		
		-40	13.1	0	0.06		
		-40	29.5	5	0.279		
		-20	20.2	5	0.142		
		-20	25.1	5	0.254		
		-10	84.8	20	1.376		
		-10	92.8	25	1.19		
		-5	29.3	5	0.389		
		-5	125.0	55	1.89		

Table B Charpy impact test data (3/6)

(T_{41J}: Charpy 41 J temperature, USE: Upper-shelf energy)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	Absorbed energy (J)	Shear fracture (%)	Lateral Expansion (mm)	T_{41J} (°C)	USE (J)
JRQ	0	12	78.7	20	1.267	-25	194
		12	103.5	30	1.434		
		40	138.6	50	2.063		
		40	147.3	80	2.005		
		60	162.2	90	2.21		
		100	179.4	100	2.431		
		100	201.4	100	2.577		
		120	199.8	100	2.395		
	2.4 @290ºC	-20	7.2	0	0.214	55	130
		19	13.2	7	0.276		
		40	8.5	9	0.220		
		40	7.9	10	0.260		
		50	51.5	26	0.898		
		50	44.2	25	0.797		
		60	57.9	27	1.013		
		80	80.0	45	1.283		
		100	77.1	56	1.501		
		140	131.6	100	2.052		
		160	141.0	100	2.146		
		160	117.3	100	1.857		
	10 @290ºC	20	5.4	0	0.120	161	111
		20	3.2	0	0.097		
		20	17.0	7	0.047		
		90	2.2	10	0.264		
		90	2.2	42	0.827		
		90	2.2	50	0.799		
		175	67.4	70	1.283		
		200	67.7	86	1.108		
		200	74.3	89	1.322		
		230	109.3	100	1.732		
		230	111.1	100	1.862		
		230	113.4	100	2.028		

Table B Charpy impact test data (4/6)

(T_{41J}: Charpy 41 J temperature, USE: Upper-shelf energy)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	Absorbed energy (J)	Shear fracture (%)	Lateral Expansion (mm)	T_{41J} (°C)	USE (J)
Steel L	0	-80	6	0	0.03	-68	189
		-80	11	0	0.02		
		-80	12.9	0	0.072		
		-80	21	0	0.16		
		-70	15	10	0.4		
		-70	42	15	0.5		
		-70	56	20	0.71		
		-65	39	10	0.47		
		-60	15	10	0.12		
		-60	40.6	5	0.445		
		-60	46	15	0.53		
		-60	54	30	0.69		
		-60	59	20	0.78		
		-60	84	30	1.11		
		-55	54	15	0.69		
		-50	79	30	1.03		
		-50	90	30	1.21		
		-50	103	35	1.39		
		-40	94.5	45	1.446		
		-40	103	35	1.41		
		-40	137	45	1.79		
		-20	112	50	1.48		
		-20	131	55	1.68		
		-20	133.1	50	1.899		
		0	134	60	1.84		
		0	148	70	1.87		
		11.6	161	80	2.181		
		20	191	100	2.17		
		20	196	100	2.35		
		40	178.8	100	2.219		

Table B Charpy impact test data (5/6)

(T_{41J}: Charpy 41 J temperature, USE: Upper-shelf energy)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	Absorbed energy (J)	Shear fracture (%)	Lateral Expansion (mm)	T_{41J} (°C)	USE (J)
Steel L	2.9 @290ºC	-40	12.5	9	0.321	12	151
		-20	13.2	12	0.322		
		0	39.7	23	0.711		
		15	45.8	31	0.923		
		28.3	54.7	38	0.951		
		50	95.8	56	1.684		
		70	143.3	100	2.257		
		100	158.1	100	2.340		
JSPS	0	-50	5.4	0		39	74
		-20	11				
		0	16.5				
		20.5	27.9	20			
		23.7	27.7	20			
		40	37.3	50			
		50	45.4				
		60	58.1	80			
		80	70.1	100			
		100	78.5	100			

Table B Charpy impact test data (6/6)

(T_{41J}: Charpy 41 J temperature, USE: Upper-shelf energy)

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Test temp. (°C)	Absorbed energy (J)	Shear fracture (%)	Lateral Expansion (mm)	T_{41J} (°C)	USE (J)
SAW CL	0	-130	22.9			-63	76
		-100	34.5				
		-50	38.9				
		-20	52.8				
		13	69.9				
		50	71.5				
		100	76.8				
		150	76.0				
	12 @290ºC	-100	14.7			-27	59
		-50	32.3				
		-20	44.1				
		21	51.0				
		100	58.8				
ESW CL	0	-130	37.0			-110	128
		-100	50.0				
		-50	61.5				
		-20	91.1				
		13	118.1				
		50	116.4				
		100	128.2				
		150	126.8				
ESW CL	15 @290ºC	-100	16.7			-55	95
		-50	46.1				
		-20	60.8				
		21	77.4				
		100	95.1				

Table C Fracture toughness test data (1/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel A	0	Mini-C (T)	4.05	4.09	8.01	-90	0.5	66.7	49.5
			4.06	4.20	8.02	-100	1.8	69.8	51.5
			4.05	4.11	8.01	-90	0.5	70.8	52.1
			4.08	4.03	8.01	-100	0.1	72.0	52.9
			4.06	4.04	8.00	-100	1.8	72.3	53.1
			4.08	4.09	8.01	-100	0.1	75.4	55.1
			4.08	4.04	8.01	-100	0.5	79.0	57.3
			4.08	4.00	8.01	-100	0.5	83.0	59.9
			4.08	4.02	8.01	-100	0.1	84.0	60.5
			4.06	4.12	8.00	-100	1.8	86.2	61.8
			4.06	4.06	8.01	-100	1.8	92.0	65.5
			4.06	4.12	8.00	-100	1.8	92.5	65.8
			4.06	4.05	8.00	-100	1.8	92.7	66.0
			4.06	4.09	8.00	-100	1.8	93.6	66.5
			4.08	4.03	8.01	-100	0.1	95.2	67.6
			4.06	4.11	8.00	-100	1.8	95.9	68.0
			4.08	4.04	8.01	-100	0.1	96.7	68.5
			4.05	4.07	8.01	-90	0.5	96.9	68.6
			4.06	4.15	8.00	-100	1.8	97.3	68.9
			4.05	4.04	8.01	-90	0.5	100.4	70.8
			4.06	4.13	8.00	-100	1.8	104.5	73.4
			4.05	4.15	8.01	-90	0.5	109.7	76.7
			4.08	4.06	8.01	-100	0.1	118.6	82.5
			4.08	4.08	8.01	-100	0.1	120.7	83.7
			4.08	4.15	8.01	-100	0.1	125.9	87.0
			4.08	4.08	8.01	-100	0.1	126.4	87.4
			4.08	4.05	8.00	-100	0.5	126.7	87.6
			4.05	4.11	8.01	-90	0.5	137.5 [132.4]	91.0*1)
			4.05	4.12	8.02	-90	0.5	184.6 [132.4]	91.0*1)

Table C Fracture toughness test data (2/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel A	0	PCCv	10.00	5.11	10.03	-100	1.0	57.9	50.1
			10.00	4.99	10.05	-90	1.0	60.8	52.4
			10.00	4.67	10.05	-90	1.0	64.7	55.6
			10.00	5.05	10.02	-100	1.0	66.7	57.2
			10.00	4.98	10.02	-100	1.0	72.7	61.9
			10.00	5.15	10.03	-100	1.0	75.6	64.3
			10.00	5.05	10.03	-100	1.0	76.2	64.7
			10.01	5.09	10.01	-80	1.0	78.3	66.4
			10.00	4.96	10.01	-80	1.0	78.5	66.5
			10.00	4.98	10.02	-100	1.0	82.4	69.7
			10.01	5.02	10.01	-80	1.0	85.0	71.7
			10.00	5.33	10.03	-100	1.0	86.5	72.9
			10.00	5.01	10.03	-90	1.0	86.5	73.0
			10.00	4.80	10.05	-90	1.0	89.0	74.9
			10.00	5.00	10.03	-100	1.0	91.9	77.2
			10.00	4.76	10.08	-90	1.0	93.1	78.1
			10.00	4.86	10.07	-90	1.0	94.6	79.4
			10.01	5.12	10.01	-80	1.0	96.6	81.0
			10.02	5.10	10.01	-80	1.0	99.5	83.3
			10.00	4.91	10.03	-90	1.0	100.8	84.3
			9.99	5.07	9.99	-80	1.0	103.5	86.4
			10.00	5.09	10.02	-100	1.0	104.9	87.5
			10.00	5.02	10.02	-100	1.0	107.5	89.6
			10.00	4.91	10.00	-90	1.0	109.8	91.4
			10.00	5.00	10.00	-80	1.0	110.8	92.3
			10.00	4.98	10.02	-80	1.0	111.9	93.1
			10.01	5.18	10.01	-80	1.0	112.0	93.2
			10.00	4.94	10.08	-90	1.0	113.1	94.1
			10.00	5.02	10.03	-80	1.0	113.3	94.2
			10.00	5.01	10.06	-90	1.0	115.0	95.6

Table C Fracture toughness test data (3/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

$^{*1)}$ $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel A	0	PCCv	10.00	5.07	10.03	-80	1.0	118.8	98.7
			10.01	5.08	10.02	-80	1.0	122.6	101.7
			10.00	5.04	10.03	-80	1.0	125.3	103.8
			10.01	5.21	10.01	-80	1.0	127.7	105.7
			10.00	5.16	10.02	-80	1.0	139.6 [135.6]	111.9$^{*1)}$
			10.02	5.15	10.02	-80	1.0	139.6 [135.5]	112.0$^{*1)}$
			10.00	5.13	10.03	-80	1.0	145.3 [136.1]	112.4$^{*1)}$
			10.00	5.16	10.01	-80	1.0	148.1 [135.3]	111.8$^{*1)}$
			10.01	5.25	10.01	-80	1.0	156.9 [134.0]	110.7$^{*1)}$
			10.00	5.01	10.01	-80	1.0	173.1 [137.4]	113.4$^{*1)}$
			10.01	5.13	10.01	-80	1.0	174.7 [135.7]	112.1$^{*1)}$
			10.01	5.14	10.01	-80	1.0	202.3 [135.6]	111.9$^{*1)}$
		1T-C (T)	25.02	29.64	50.04	-80	0.8	64.2	64.0
			25.00	28.59	49.99	-80	0.8	69.9	69.7
			25.00	28.57	50.01	-80	0.8	72.6	72.4
			24.99	28.73	50.00	-80	0.8	73.5	73.2
			25.00	28.55	50.00	-80	0.8	79.6	79.4
			25.00	28.77	50.00	-80	0.8	85.2	84.9
			25.02	29.08	50.00	-80	0.8	87.5	87.2
			25.00	29.30	50.02	-50	0.8	94.4	94.1
			25.02	29.24	50.02	-80	0.8	97.0	96.7
			25.02	29.05	50.02	-80	0.8	99.3	99.0
			24.99	28.55	50.00	-80	0.8	102.2	101.9
			25.00	29.32	50.02	-80	0.8	109.6	109.3
			25.02	29.21	50.02	-50	0.8	88.5	88.3

Table C Fracture toughness test data (4/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel A	0	1T-C (T)	25.02	29.54	50.02	-50	0.8	106.3	106.0
			25.00	28.59	49.99	-50	0.8	111.0	110.6
			25.00	29.06	50.02	-50	0.8	116.0	115.7
			25.02	29.22	50.00	-50	0.8	120.3	119.9
			25.00	29.37	50.02	-50	0.8	130.6	130.2
			25.02	29.01	50.04	-50	0.8	133.2	132.8
			25.00	28.54	49.99	-50	0.8	138.4	137.9
			25.00	29.10	49.97	-50	0.8	142.8	142.3
			25.00	28.46	50.00	-50	0.8	147.4	146.9
			24.99	28.71	50.00	-50	0.8	154.5	154.0
			25.00	28.64	50.05	-50	0.8	170.9	170.3
			24.99	28.83	49.97	-30	0.8	138.7	138.2
			25.00	29.16	50.05	-30	0.8	151.1	150.6
			25.00	28.90	49.98	-30	0.8	153.9	153.4
			25.00	29.03	49.98	-30	0.8	162.2	161.6
			24.99	28.78	50.02	-30	0.8	178.0	177.3
			25.00	28.92	50.04	-30	0.8	187.6	187.0
			25.00	29.02	50.07	-30	0.8	188.6	187.9
			25.00	28.90	50.00	-30	0.8	223.1	222.3
		4T-C (T)	101.2	106.15	200.3	-80	0.1	75.8	99.1
			100.0	105.64	200.5	-50	0.1	96.7	128.4
			101.4	106.63	200.4	-50	0.1	102.8	137.5

Table C Fracture toughness test data (5/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel A	13 @290ºC	PCCv	9.98	5.21	9.99	50	1.0	52.1	45.5
			9.99	5.12	9.99	50	1.0	57.4	49.7
			9.99	5.05	9.99	50	1.0	60.2	52.0
			9.99	5.07	9.99	50	1.0	62.5	53.8
			9.99	5.02	9.99	50	1.0	68.5	58.6
			9.98	5.11	9.98	50	1.0	71.7	61.1
			9.99	5.09	9.99	50	1.0	90.9	76.3
			9.99	5.12	9.99	50	1.0	143.8	118.4
Steel B	0	Mini-C (T)	4.08	4.05	8.01	-120	1.8	48.4	38.0
			4.05	4.05	8.02	-120	0.5	61.2	46.0
			4.07	4.04	8.00	-120	1.8	67.5	50.1
			4.05	4.13	8.01	-120	0.1	70.2	51.7
			4.08	4.06	8.01	-120	1.8	77.7	56.5
			4.05	4.07	8.00	-120	0.5	78.6	57.0
			4.05	4.14	8.01	-120	0.1	78.9	57.2
			4.05	4.13	8.01	-120	0.1	82.8	59.7
			4.05	4.11	8.01	-120	0.1	83.1	59.9
			4.08	4.04	8.01	-120	1.8	83.2	60.0
			4.04	4.11	8.01	-120	0.1	86.4	61.9
			4.08	4.07	8.01	-120	1.8	88.3	63.2
			4.05	4.09	8.01	-120	0.5	89.5	63.9
			4.05	4.18	8.01	-120	0.1	89.5	63.9
			4.08	4.11	8.00	-120	1.8	91.0	64.9
			4.05	4.10	8.01	-120	0.1	91.8	65.4
			4.08	4.07	8.00	-120	1.8	91.8	65.4
			4.08	4.08	8.01	-120	1.8	93.8	66.7
			4.08	4.05	8.01	-120	1.8	93.8	66.7
			4.05	4.11	8.01	-120	0.5	96.7	68.5
			4.06	4.00	8.01	-120	0.5	103.3	72.7
			4.04	4.10	8.01	-120	0.1	110.6	77.2

Table C Fracture toughness test data (6/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel B	0	Mini-C (T)	4.08	4.10	8.01	-120	1.8	115.3	80.3
			4.05	4.18	8.01	-120	0.1	115.6	80.4
			4.05	4.07	8.01	-120	0.5	128.0	88.3
			4.06	4.08	8.01	-120	0.5	129.8	89.4
			4.05	4.12	8.00	-120	0.1	131.9	90.7
			4.06	4.05	8.00	-120	0.5	132.6	91.2
			4.06	4.13	8.01	-120	0.5	134.9	92.7
			4.06	4.09	8.01	-120	0.5	162.4 [142.2]	97.2*1)
		PCCv	10.00	4.80	10.00	-130	1.0	47.5	41.9
			10.02	4.85	10.00	-110	1.0	63.2	54.4
			10.00	5.04	10.00	-120	1.0	64.1	54.9
			10.02	5.01	10.01	-110	1.0	73.2	62.3
			10.00	4.93	10.03	-130	1.0	59.5	51.4
			10.00	5.01	10.03	-130	1.0	61.5	53.0
			10.00	4.98	10.00	-120	1.0	69.0	58.7
			10.01	5.07	10.00	-120	1.0	73.8	62.5
			10.01	4.80	10.05	-120	1.0	74.7	63.2
			9.99	4.85	10.00	-120	1.0	79.4	66.8
			10.01	4.87	10.00	-130	1.0	72.8	62.0
			10.01	4.81	10.05	-110	1.0	92.7	77.9
			10.01	4.85	10.00	-110	1.0	93.1	78.2
			10.00	4.97	10.00	-130	1.0	74.0	62.9
			10.01	4.84	10.04	-130	1.0	74.0	62.9
			10.01	4.81	10.00	-110	1.0	94.2	79.1
			10.00	4.88	10.03	-120	1.0	84.1	70.5
			10.00	5.01	10.04	-120	1.0	84.2	70.5
			10.00	4.87	10.00	-130	1.0	75.0	63.7
			10.01	5.12	10.02	-130	1.0	76.5	64.9
			10.01	5.15	10.01	-130	1.0	83.5	70.5
			10.01	5.23	10.02	-130	1.0	84.2	71.1

Table C Fracture toughness test data (7/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel B	0	PCCv	10.02	4.92	10.03	-120	1.0	97.9	81.2
			10.03	4.79	10.01	-120	1.0	102.6	84.8
			10.00	4.74	10.02	-110	1.0	119.9	99.5
			10.02	5.13	10.02	-110	1.0	122.6	101.6
			10.02	5.18	10.01	-120	1.0	112.0	92.1
			10.00	4.96	10.01	-110	1.0	134.2	110.8
			10.01	5.07	10.01	-110	1.0	140.8	116.1
			10.02	5.08	10.01	-110	1.0	149.4 [116.9]	119.3*1)
			10.01	5.25	10.02	-110	1.0	152.0 [116.9]	117.4*1)
			10.02	5.30	10.02	-110	1.0	228.3 [116.9]	116.9*1)
		1T-C (T)	25.00	28.59	50.02	-110	0.8	65.2	65.0
			25.04	28.67	50.02	-110	0.8	71.0	70.9
			25.00	29.12	50.02	-110	0.8	71.1	70.9
			25.02	29.17	50.02	-110	0.8	78.1	77.9
			25.02	29.73	50.02	-110	0.8	79.6	79.4
			25.02	28.96	50.00	-110	0.8	87.6	87.4
			25.00	28.63	50.01	-110	0.8	97.7	97.4
			25.04	28.98	50.00	-110	0.8	99.3	99.0
			24.99	29.38	50.00	-110	0.8	104.3	104.0
			25.02	29.31	50.02	-110	0.8	108.0	107.7
			25.00	29.27	50.04	-110	0.8	110.5	110.1
			25.00	28.79	50.03	-110	0.8	120.8	120.4
			25.02	29.06	50.02	-80	0.8	72.3	72.1
			25.00	28.81	50.01	-80	0.8	88.4	88.1
			25.02	29.22	50.02	-80	0.8	94.2	93.9
			25.00	29.22	50.01	-80	0.8	105.4	105.1
			25.02	29.35	50.00	-80	0.8	122.8	122.5
			25.00	28.54	50.00	-80	0.8	124.6	124.2
			24.99	28.74	50.02	-80	0.8	132.8	132.3

Table C Fracture toughness test data (8/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel B	0	1T-C(T)	25.02	29.48	50.00	-80	0.8	134.1	133.7
			25.02	29.08	50.02	-80	0.8	135.2	134.8
			25.04	28.88	50.02	-80	0.8	136.4	136.0
			25.00	29.40	50.02	-80	0.8	136.9	136.4
			25.00	28.43	50.00	-80	0.8	158.6	158.0
			25.00	28.80	50.00	-60	0.8	122.8	122.3
			25.00	29.18	50.06	-60	0.8	123.4	123.0
			25.00	29.27	50.06	-60	0.8	155.0	154.4
			25.00	28.89	50.02	-60	0.8	157.4	156.8
			25.00	29.15	50.06	-60	0.8	184.7	184.1
			25.00	29.06	50.07	-60	0.8	210.6	209.8
			25.00	29.19	50.02	-60	0.8	211.0	210.2
			25.00	29.17	50.02	-60	0.8	226.8	226.0
		4T-C (T)	101.5	106.39	200.4	-110	0.1	55.9	71.0
			101.5	108.93	200.2	-80	0.1	69.6	90.5
			101.3	106.99	200.2	-80	0.1	102.6	137.2
Steel B	11 @290ºC	PCCv	9.99	5.04	10.00	-50	1.0	44.8	39.7
			9.98	4.96	9.98	-50	1.0	55.2	48.0
			9.99	4.91	9.99	-50	1.0	61.9	53.3
			9.98	5.10	9.98	-50	1.0	92.8	77.9
			9.99	5.10	9.99	-50	1.0	94.6	79.3
			9.98	5.06	9.98	-50	1.0	108.7	90.5
			10.00	5.04	10.01	-50	1.0	112.2	93.3

Table C Fracture toughness test data (9/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
JRQ	0	Mini-C (T)	4.08	3.98	8.00	-100	0.5	116.2	80.9
			4.08	3.98	8.00	-100	0.5	76.7	55.9
			4.08	4.03	8.01	-100	0.5	102.6	72.3
			4.08	4.09	8.01	-100	0.5	100.8	71.2
			4.08	4.05	8.01	-100	0.5	65.2	48.6
			4.08	4.00	8.01	-100	0.5	153.6 [139.6]	95.7*1)
			4.08	4.07	8.00	-110	0.5	67.1	49.8
			4.08	4.04	8.01	-110	0.5	140.3	96.2
			4.08	4.06	8.02	-110	0.5	121.6	84.3
			4.08	4.05	8.02	-110	0.5	82.9	59.8
			4.08	4.03	8.01	-110	0.5	99.7	70.5
			4.07	4.06	8.01	-110	0.5	59.0	44.7
		PCCv	10.00	5.06	10.00	-80	1.0	39.9	35.8
			10.00	4.97	10.02	-80	1.0	72.6	61.8
			10.00	5.60	10.00	-80	1.0	86.0	72.5
			10.00	5.58	10.00	-80	1.0	86.2	72.6
			10.00	5.60	10.00	-80	1.0	89.7	75.4
			10.00	4.90	10.01	-80	1.0	92.6	77.7
			10.00	5.64	10.00	-80	1.0	92.9	78.0
			10.00	5.61	10.00	-80	1.0	93.0	78.1
			10.00	4.93	10.00	-80	1.0	99.0	82.8
			10.00	4.95	10.00	-80	1.0	110.0	91.5
			10.00	5.07	10.00	-80	1.0	115.7	96.1
			10.00	5.78	10.00	-80	1.0	119.9	99.4
			10.00	4.96	10.00	-80	1.0	120.3	99.7
			10.00	5.54	10.00	-80	1.0	121.3	100.6
			10.00	5.01	10.00	-80	1.0	125.6	104.0
			10.00	5.64	10.00	-80	1.0	127.3	105.3

Table C Fracture toughness test data (10/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
JRQ	0	0.4T-C (T)	10.03	10.97	20.00	-80	0.5	109.7	91.1
			10.03	11.11	20.01	-80	0.5	79.4	67.1
			10.03	11.02	20.01	-80	0.5	101.8	84.8
			10.03	11.08	20.01	-80	0.5	94.5	79.0
			10.03	10.97	20.01	-80	0.5	116.2	96.3
			10.03	11.03	20.00	-80	0.5	126.6	104.5
			10.03	11.03	20.00	-80	0.5	111.2	92.3
			10.03	11.12	20.00	-80	0.5	129.1	106.5
			10.03	11.08	20.01	-50	0.5	128.1	105.7
			10.03	11.05	20.00	-50	0.5	161.6	132.3
			10.03	11.08	20.00	-50	0.5	171.4	140.0
			10.03	11.06	20.00	-50	0.5	171.6	140.2
			10.03	11.07	20.01	-50	0.5	136.8	112.6
			10.03	11.09	20.01	-50	0.5	138.1	113.6
			10.03	11.17	20.01	-50	0.5	81.2	68.5
		1T-C (T)	25.0	25.64	50.00	-80	0.8	50.2	50.1
			25.0	25.63	50.00	-80	0.8	61.6	61.5
			25.0	25.67	50.00	-80	0.8	65.5	65.3
			25.0	25.42	50.00	-80	0.8	76.3	76.1
			25.0	25.59	50.00	-80	0.8	80.4	80.1
			25.0	25.57	50.00	-80	0.8	122.0	121.6
			25.0	25.58	50.00	-50	0.8	136.1	135.6
			25.0	25.47	50.00	-50	0.8	100.4	100.1
			25.0	25.31	50.00	-50	0.8	144.8	144.3

Table C Fracture toughness test data (11/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
JRQ	11 @290ºC	PCCv	10.02	5.23	10.03	100	1.0	57.0	49.4
			10.01	5.26	10.03	100	1.0	64.0	55.0
			10.02	5.11	10.03	100	1.0	64.7	55.6
			10.02	5.13	10.03	100	1.0	68.1	58.3
			10.02	5.02	10.03	100	1.0	74.0	63.0
			10.02	5.08	10.02	100	1.0	80.9	68.4
			10.02	5.12	10.03	100	1.0	100.0	83.7
			10.02	5.18	10.03	100	1.0	109.6	91.3

Table C Fracture toughness test data (12/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel L	0	PCCv	10.01	5.11	10.02	-130	1.0	67.5	57.8
			10.00	4.93	10.02	-130	1.0	73.3	62.4
			10.02	4.97	10.04	-130	1.0	82.4	69.6
			10.03	5.03	10.03	-130	1.0	91.3	76.7
			10.02	4.99	10.03	-130	1.0	94.6	79.4
			10.03	5.03	10.01	-130	1.0	100.3	83.9
			10.00	5.05	10.01	-130	1.0	101.6	84.9
			10.02	5.10	10.01	-130	1.0	113.3	94.2
			10.01	5.14	10.03	-130	1.0	114.2	94.9
			10.01	5.05	10.01	-130	1.0	127.4	105.4
			10.01	4.91	10.01	-100	1.0	117.2	97.3
			10.00	5.03	10.01	-100	1.0	120.3	99.8
			10.01	5.13	10.01	-100	1.0	128.8	106.6
			10.02	5.11	10.02	-100	1.0	135.5	111.9
			10.01	5.00	10.02	-100	1.0	140.4	115.8
			10.01	4.92	10.01	-100	1.0	158.5 [142.5]	117.4*1)
			10.01	5.10	10.02	-100	1.0	170.4 [140.2]	115.6*1)
			10.01	5.09	10.01	-100	1.0	192.0 [140.2]	115.6*1)
			10.02	4.87	10.01	-100	1.0	198.8 [143.2]	118.0*1)
			10.00	5.10	10.02	-100	1.0	199.8 [140.2]	115.6*1)
			10.01	4.88	10.01	-100	1.0	213.3 [143.2]	118.0*1)
			10.00	5.03	10.01	-100	1.0	213.5 [141.0]	116.2*1)

Table C Fracture toughness test data (13/13)

(B: Specimen thickness; a0: Crack length; W: Specimen width)

*1) $K_{Jc(1Teq)}$ was calcrated from $K_{Jc(limit)}$ as a censored K_{Jc} according to ASTM E1921.

Material ID	Fluence (10^{19} n/cm^2) E>1 MeV	Specimen type	B (mm)	a_0 (mm)	W (mm)	Test temp. (°C)	dK/dt (MPa√m/s)	K_{Jc} [$K_{Jc(limit)}$] (MPa√m)	$K_{Jc(1Teq)}$ (MPa√m)
Steel L	0	1T-C (T)	24.99	25.68	49.99	-100	0.8	61.8	61.6
			24.99	25.59	49.96	-100	0.8	105.7	105.3
			24.99	25.93	49.99	-100	0.8	115.3	114.9
			24.98	25.71	49.92	-100	0.8	141.2	140.7
			24.99	25.72	50.05	-100	0.8	150.4	149.8
			24.99	25.83	49.96	-100	0.8	170.8	170.2
	2.9 @290ºC	PCCv	10.01	5.25	10.00	-40	1.0	78.2	66.3
			10.02	5.61	10.00	-40	1.0	78.6	66.6
			10.02	5.36	10.00	-40	1.0	81.7	69.1
			10.02	5.29	10.00	-40	1.0	92.7	77.9
			10.02	5.34	10.00	-40	1.0	95.4	80.0
			10.01	5.37	10.00	-40	1.0	103.2	86.2
			10.02	5.63	10.00	-40	1.0	104.6	87.3
			10.02	5.40	10.00	-40	1.0	105.8	88.3
			10.02	5.49	10.00	-40	1.0	106.5	88.8
			10.02	5.37	10.00	-40	1.0	108.9	90.7
			10.02	5.29	10.00	-40	1.0	125.7	104.1
			10.02	5.25	10.00	-40	1.0	131.5	108.7
JSPS	0	PCCv	10.01	4.84	10.00	-25	1.0	63.9	54.8
			10.00	4.95	10.00	-25	1.0	75.3	63.8
			10.01	4.91	10.00	-25	1.0	79.2	66.9
			10.00	5.29	9.99	-25	1.0	82.1	69.2
			10.01	4.93	10.01	-25	1.0	83.4	70.3
			10.01	4.99	10.00	-25	1.0	89.0	74.7
			10.01	4.85	10.01	-25	1.0	109.6	91.0
			10.01	4.85	10.01	-25	1.0	114.5	94.9

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 組立単位	
	名称	記号
面積	平方メートル	m^2
体積	立方メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度[a]，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立方メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率[b]	（数字の）1	1
比透磁率[b]	（数字の）1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[b]	rad	1 [b]	m/m
立体角	ステラジアン[b]	sr[c]	1 [b]	m^2/m^2
周波数	ヘルツ[d]	Hz		s^{-1}
力	ニュートン	N		$m\ kg\ s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1}\ kg\ s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N m	$m^2\ kg\ s^{-2}$
仕事率，工率，放射束	ワット	W	J/s	$m^2\ kg\ s^{-3}$
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	$m^2\ kg\ s^{-3}\ A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2}\ kg^{-1}\ s^4\ A^2$
電気抵抗	オーム	Ω	V/A	$m^2\ kg\ s^{-3}\ A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2}\ kg^{-1}\ s^3\ A^2$
磁束	ウエーバ	Wb	Vs	$m^2\ kg\ s^{-2}\ A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg\ s^{-2}\ A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2\ kg\ s^{-2}\ A^{-2}$
セルシウス温度	セルシウス度[e]	℃		K
光束	ルーメン	lm	cd sr[c]	cd
照度	ルクス	lx	lm/m^2	$m^{-2}\ cd$
放射性核種の放射能[f]	ベクレル[d]	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	$m^2\ s^{-2}$
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト[g]	Sv	J/kg	$m^2\ s^{-2}$
酸素活性	カタール	kat		$s^{-1}\ mol$

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	$m^{-1}\ kg\ s^{-1}$
力のモーメント	ニュートンメートル	N m	$m^2\ kg\ s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg\ s^{-2}$
角速度	ラジアン毎秒	rad/s	$m\ m^{-1}\ s^{-1}=s^{-1}$
角加速度	ラジアン毎秒毎秒	rad/s^2	$m\ m^{-1}\ s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg\ s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2\ kg\ s^{-2}\ K^{-1}$
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	$m^2\ s^{-2}\ K^{-1}$
比エネルギー	ジュール毎キログラム	J/kg	$m^2\ s^{-2}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	$m\ kg\ s^{-3}\ K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1}\ kg\ s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m\ kg\ s^{-3}\ A^{-1}$
電荷密度	クーロン毎立方メートル	C/m^3	$m^{-3}\ s\ A$
表面電荷	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
電束密度，電気変位	クーロン毎平方メートル	C/m^2	$m^{-2}\ s\ A$
誘電率	ファラド毎メートル	F/m	$m^{-3}\ kg^{-1}\ s^4\ A^2$
透磁率	ヘンリー毎メートル	H/m	$m\ kg\ s^{-2}\ A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2\ kg\ s^{-2}\ mol^{-1}$
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	$m^2\ kg\ s^{-2}\ K^{-1}\ mol^{-1}$
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1}\ s\ A$
吸収線量率	グレイ毎秒	Gy/s	$m^2\ s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4\ m^{-2}\ kg\ s^{-3}=m^2\ kg\ s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2\ sr)$	$m^2\ m^{-2}\ kg\ s^{-3}=kg\ s^{-3}$
酵素活性濃度	カタール毎立方メートル	kat/m^3	$m^{-3}\ s^{-1}\ mol$

表５．SI 接頭語

乗数	名称	記号	乗数	名称	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60 s
時	h	1 h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10 800) rad
秒	”	1”=(1/60)’=(π/648 000) rad
ヘクタール	ha	$1\ ha=1\ hm^2=10^4 m^2$
リットル	L，l	$1\ L=1\ l=1\ dm^3=10^3 cm^3=10^{-3} m^3$
トン	t	$1\ t=10^3\ kg$

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	$1\ eV=1.602\ 176\ 53(14)\times10^{-19} J$
ダルトン	Da	$1\ Da=1.660\ 538\ 86(28)\times10^{-27} kg$
統一原子質量単位	u	1 u=1 Da
天文単位	ua	$1\ ua=1.495\ 978\ 706\ 91(6)\times10^{11} m$

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	$1\ bar=0.1 MPa=100\ kPa=10^5 Pa$
水銀柱ミリメートル	mmHg	1 mmHg≈133.322Pa
オングストローム	Å	$1\ Å=0.1 nm=100 pm=10^{-10} m$
海里	M	1 M=1852m
バーン	b	$1\ b=100 fm^2=(10^{-12} cm)^2=10^{-28} m^2$
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デシベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5} N$
ポアズ	P	$1\ P=1\ dyn\ s\ cm^{-2}=0.1 Pa\ s$
ストークス	St	$1\ St=1 cm^2\ s^{-1}=10^{-4} m^2\ s^{-1}$
スチルブ	sb	$1\ sb=1 cd\ cm^{-2}=10^4 cd\ m^{-2}$
フォト	ph	$1\ ph=1 cd\ sr\ cm^{-2}=10^4 lx$
ガル	Gal	$1\ Gal=1 cm\ s^{-2}=10^{-2} ms^{-2}$
マクスウエル	Mx	$1\ Mx = 1 G\ cm^2=10^{-8} Wb$
ガウス	G	$1\ G=1 Mx\ cm^{-2}=10^{-4} T$
エルステッド[a]	Oe	$1\ Oe ≙ (10^3/4\pi) A\ m^{-1}$

(a) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	$1\ Ci=3.7\times10^{10} Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4} C/kg$
ラド	rad	$1\ rad=1 cGy=10^{-2} Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2} Sv$
ガンマ	γ	$1\ \gamma=1\ nT=10^{-9} T$
フェルミ		1 フェルミ$=1\ fm=10^{-15} m$
メートル系カラット		1 メートル系カラット＝0.2 g = $2\times10^{-4} kg$
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1 cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー），4.184J（「熱化学」カロリー）
ミクロン	µ	$1\ \mu=1 \mu m=10^{-6} m$

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