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Division I

THE POTENTIAL FOR USE OF MINI CT SPECIMENS IN OBTAINING THE FRACTURE TOUGHNESS CHARACTERISTICS OF 15KH2NMFA STEEL

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ABSTRACT

A new promising research area has emerged recently, wherein static fracture toughness parameters characterizing the brittle strength of a metal are defined when miniature specimens of CT type with overall dimensions 10×9.6×4 mm (hereinafter referred to as “mini CT specimens”) are tested for eccentric tension.

The National Research Center "Kurchatov Institute" (hereinafter referred to as NRC KI) established the process of preparation and testing of mini CT specimens, which made it possible to obtain the correct data on fracture toughness in miniature specimens. Standardizing such specimens for use in the field of reactor materials science will contribute to facilitating the acquisition of experimental data in conditions of a limited amount of research material.

The article presents the results from testing of mini CT specimens of SFVQ1A RPV steel, prepared by CRIEPI (Japan), and obtained at NRC KI. For SFVQ1A steel, there is a large amount of open source test results for mini CT specimens, such as the works of Yamamoto et al. (2014), Miura and Soneda (2010), which were used to validate the results obtained at NRC KI.

The results of using mini CT specimens of 15Kh2NMFA grade 1 steel in the initial state when compared to CT-0.5 specimens testing is demonstrated.

TEST MATERIAL

For carrying out the round robin test under the TOM project, CRIEPI Institution (Japan) selected an unirradiated forging of SFVQ1A RPV steel analogous to the US steel SA508 Cl.3. The steel chemical composition is shown in Table 1. A half of the previously tested 100-mm thick CT-4T specimen with marking F4-05 was used as a blank for cutting out the specimens.

Table 1: Chemical composition of SFVQ1A steel

Material (unit in wt. %)	C	Si	Mn	P	S	Ni	Cr	Mo	V
Target value	~0.25	~0.40	1.20~1.50	~0.025	~0.025	0.40~1.00	~0.25	0.45~0.60	~0.05
Product value	0.18	0.18	1.46	0.002	<0.001	0.90	0.12	0.52	<0.01

The blank was cut into bars 12×12×100 mm in size (each bar had its own No and marking) for the subsequent production of mini CT specimens. The scheme of cutting bars and specimens is presented in Figure 1 [Yamamoto et al. (2014)]

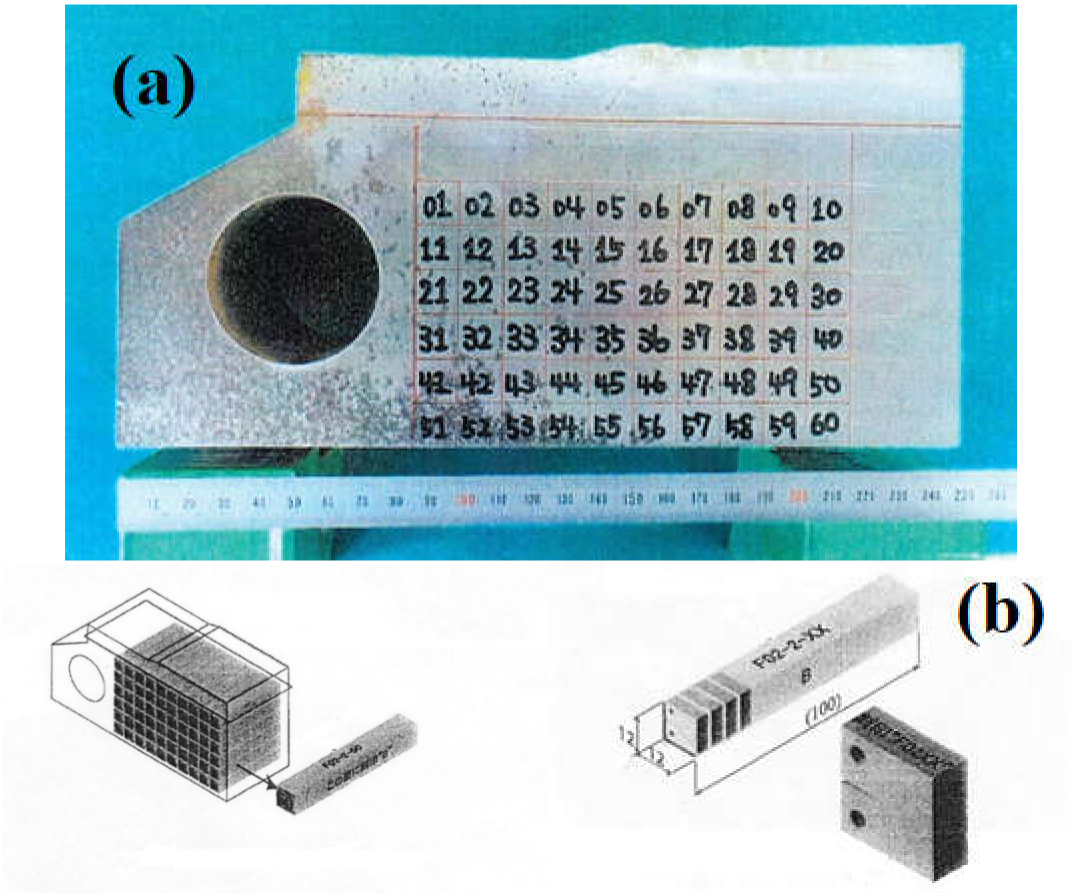

Figure 1. Photo of a half of the initial CT-4T specimen (a) and Schematic diagram of cutting mini CT specimens and bars out of the CT-4T specimen (b) [Yamamoto et al. (2014)]

A series of 20 ready-made specimens with grown fatigue cracks, as well as one bar for the production of mini CT specimens, were transferred to the NRC KI.

Thus, the test consisted of two phases: Phase 1 – the testing of specimens prepared by CRIEPI, Phase 2 – preparation of mini CT specimens by NRC KI, with initial fatigue cracks' growing and their subsequent testing.

Twenty mini CT specimens were produced out of the bar transferred to NRC KI via the electrical discharge machining. Figure 2 presents a photo of the mini CT specimen prepared at NRC KI for the fracture toughness test. Before testing, fatigue cracks were grown in accordance with the ASTM E1921 Standard.

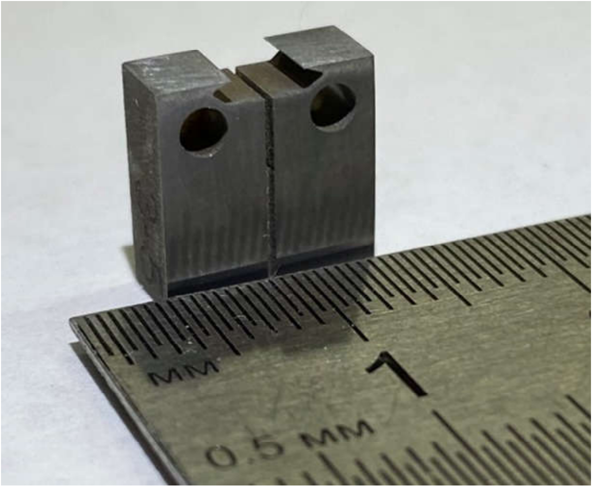

Figure 2. Mini CT sample for the fracture toughness test

TEST RESULTS

Figure 3 is a graphical representation of the results from the first phase and the second phase tests of mini CT specimens of SFVQ1A RPV steel, conducted by NRC KI.

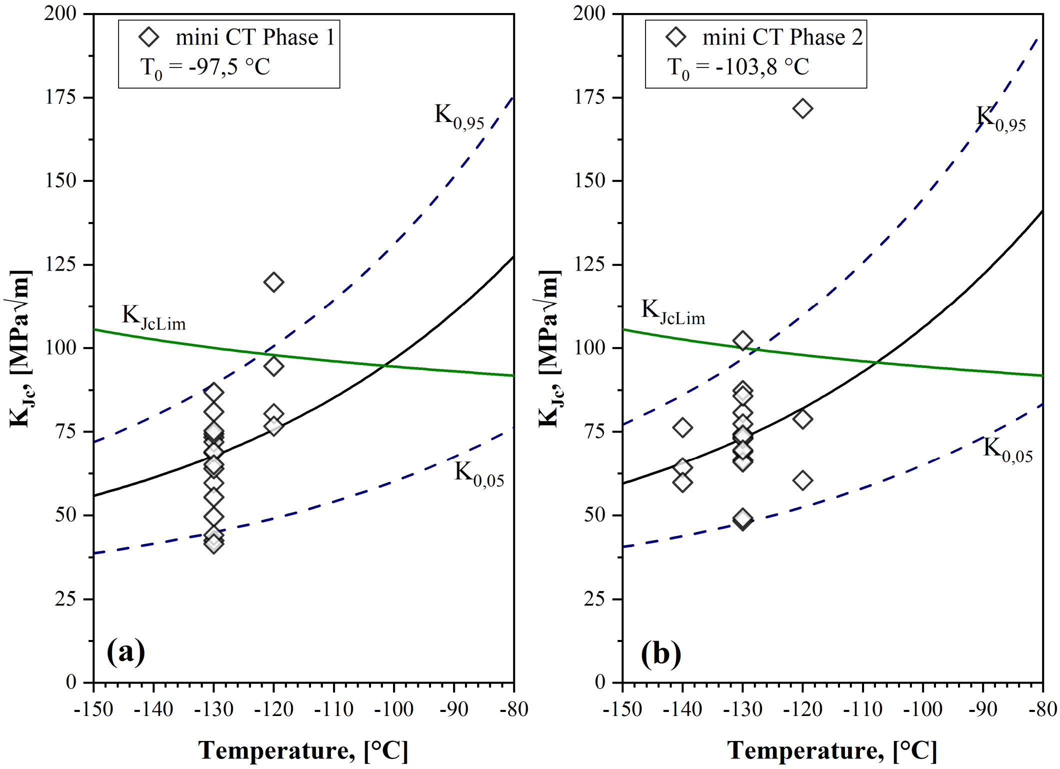

Figure 3. The results from specimen tests within the first (a) and the second (b) phase of research conducted by NRC KI

Table 2 provides values of brittle transition temperature calculated according to the ASTM E1921 Standard.

Table 2: The parameters of the ductile to brittle transition for the test material, obtained during the first and the second phase testings of mini CT specimens

Group	*Block Number*	*dK/dt MPa√m/s*	*N*	*r*	*T_0, [°C]*	$\sum r_i n_i$	*σ_{T0}, [°C]*
Phase 1	F4-5-04	1	20	19	-97.5	2.7	5.9
Phase 2	F4-5-19	1	20	18	-103.8	2.5	6.0

Note: The last two digits of the block number correspond to the block number in Figure 1 and indicate the location of the mini-CT specimen in the initial 4T-CT specimen.

As shown in Table 2, the data obtained for the both groups of specimens coincide. Figure 4 shows the correlation between the ductile to brittle transition temperatures, obtained in this work, and the temperatures obtained by Yamamoto et al. (2014).

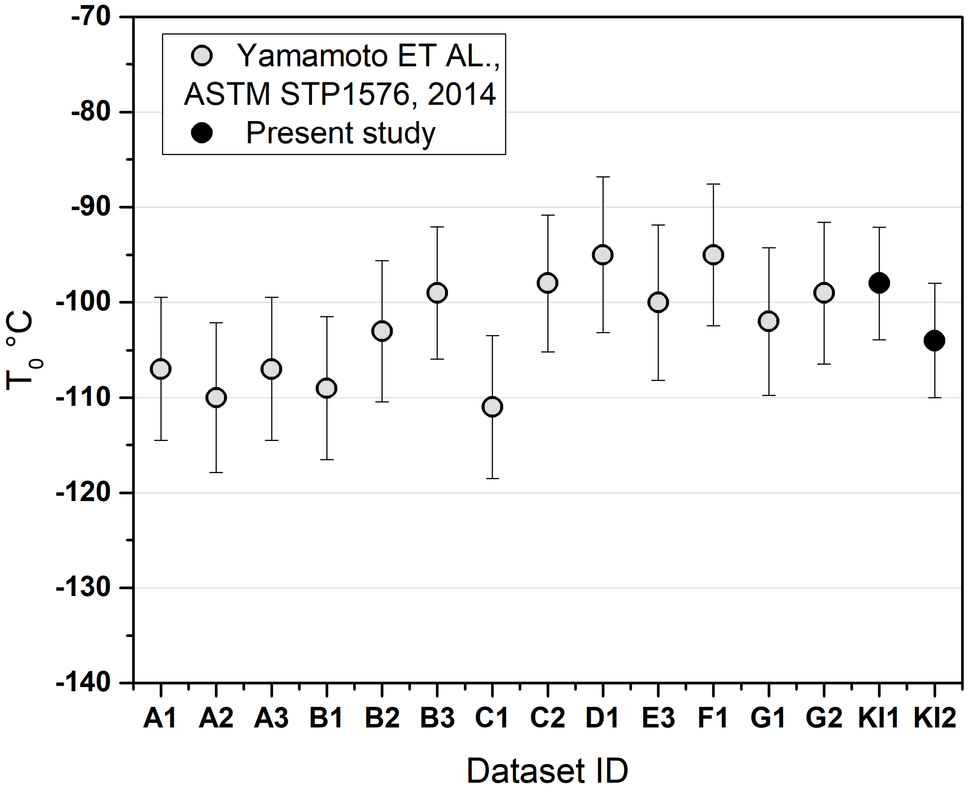

Figure 4. Comparison of T_0 with literature data.
KI1 – a value corresponding to phase 1, KI2 – a value corresponding to phase 2

As shown in Figure 4, the new points are well correlated with the previously obtained data, which once again confirms that the testing of mini CT specimens of SFVQ1A steel according to the requirements specified in the ASTM E1921 Standard makes it possible to obtain similar values of the ductile to brittle transition temperature (T_0) when performing the tests by different operators and on different machines.

According to the master curve concept, the experimentally obtained fracture toughness values follow the Weibull statistical distribution [Yamamoto et al. (2014)]:

$$p_f = 1 - \exp\left\{-\left[\frac{(K_{Jc}-20)}{(K_0-20)}\right]^n\right\}, \quad (1)$$

where p_f is the probability that an individual specimen taken from the test series will fail at the crack resistance value $K \le K_{Jc}$; n is the shape parameter equal to 4; and K_0 is the calibration parameter determined experimentally.

To assess the results obtained for correlation with the Weibull distribution, with the coefficients n=4 and K_{min}=20 MPa√м used in the ASTM E1921 standard, the dependences (1) were plotted on a logarithmic scale. The graphical representation of the dependencies is shown in Figure 5. When fitting the data obtained for the specimens prepared by NRC KI, the points where the crack resistance parameter exceeded the value $K_{Jc(lim)}$ were not taken into account.

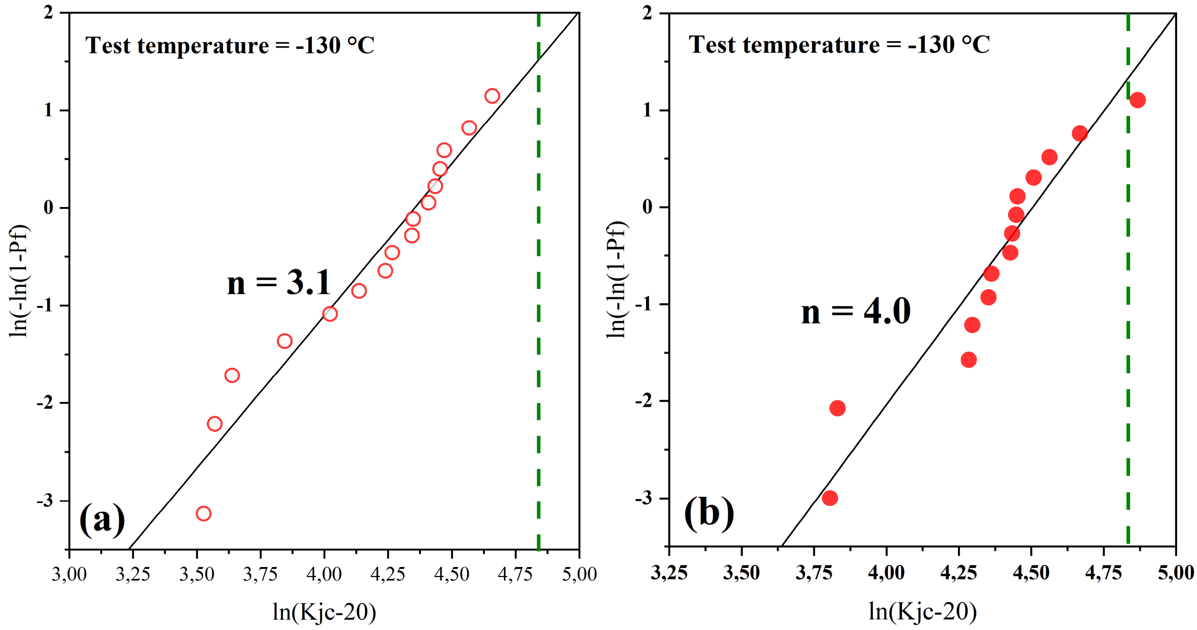

Figure 5. Weibull distribution for the set of specimens of phase 1 (a) and phase 2 (b), tested at -130°C. The dotted line on the graphs shows the $K_{Jc(lim)}$ value for a given temperature

As shown in Figure 5, the experimental data obtained on mini CT specimens of SFVQ1A steel follow the Weibull statistical distribution. Linear approximation of the points resulted in the values of coefficient n equal to 3.12 for the specimens prepared by CRIEPI, and to 4.04 for the specimens prepared by NRC KI. In case of combined processing of the both data sets: n = 3.5. The results obtained fall within the evaluated parameter limits, shown in Figure 6 (Yamamoto et al. (2014), Wallin (1984)), when the parameter is determined on a limited number of specimens. Thus, the results of mini CT specimens' testing, along with the results obtained for CT-0.5 specimens in the works, demonstrated the correctness of its use (Yamamoto et al. (2014), Wallin (1984)).

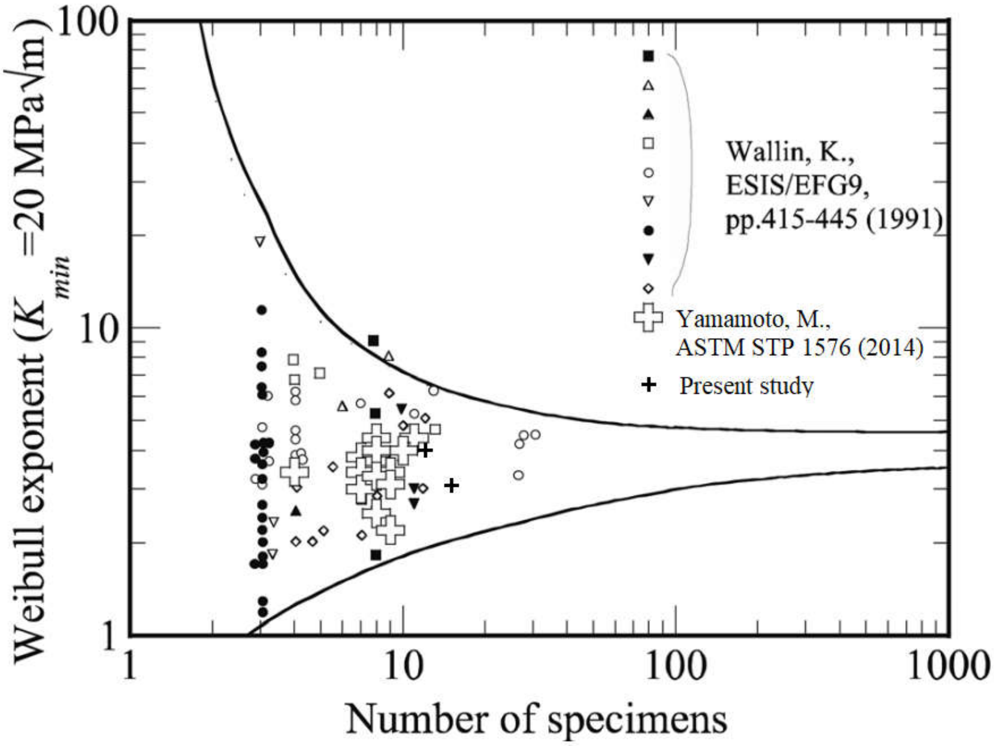

Figure 6. Experimental values of the Weibull distribution shape parameter *n* in dependence with the number of specimens within the testing series [Yamamoto et al. (2014), Wallin (1984)]

THE ISE OF MINI CT SPECIMENS IN OBTAINING THE FRACTURE TOUGHNESS CHARACTERISTICS OF 15Kh2NMFA GRADE 1 STEEL

The positive experience of testing the mini CT specimens made of SFVQ1A RPV steel was decided to carry over to the 15Kh2NMFA grade 1 steel, which is used in manufacturing of the VVER-type RPV. The use of mini CT specimens will contribute to increasing the amount of experimental data in conditions of a limited amount of research material. The chemical composition of the steel used in the manufacture of Russian VVER-1000 reactor vessels significantly differs from that of SFVQ1A steel. An industrial melting was used to determine the fracture toughness parameters of 15Kh2NMFA grade 1 steel in mini CT specimens. CT-0.5 specimens and cylindrical static tension specimens were prepared and tested using the 15Kh2NMFA grade 1 steel. Three archival CT-0.5 specimens were used for cutting the mini CT specimens in accordance with the ASTM E1921 Standard. The chemical composition of the 15Kh2NMFA grade 1 steel is presented in Table 3. Figure 7 demonstrates the photo and the scheme of cutting mini CT specimens.

Table 3: Chemical composition of the 15Kh2NMFA grade 1 steel, according to manufacturer specifications

Mass fraction. wt. %										
C	Mn	P	S	Cr	Ni	Mo	Si	V	Cu	Co
0.17	0.44	0.005	0.004	1.98	1.18	0.63	0.26	0.10	0.04	0.005

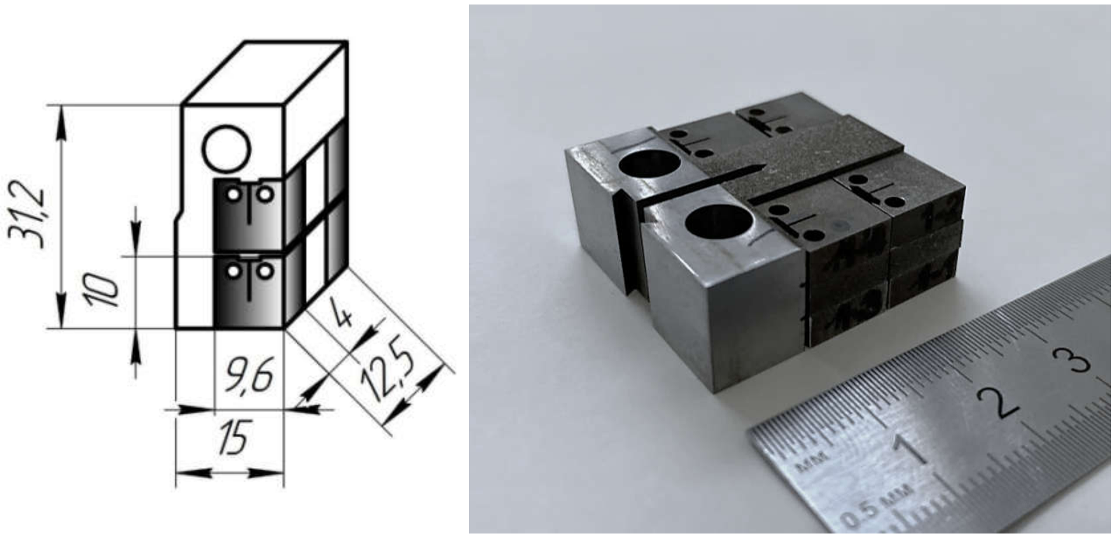

Figure 7. The scheme of cutting mini CT specimens out of the CT-0,5 type specimens

After the mini CT specimens were prepared, the fatigue cracks were grown in accordance with the ASTM E1921 Standard and the fracture toughness tests were performed. Figure 8 and Table 4 show the test results for CT-0,5 and mini CT specimens.

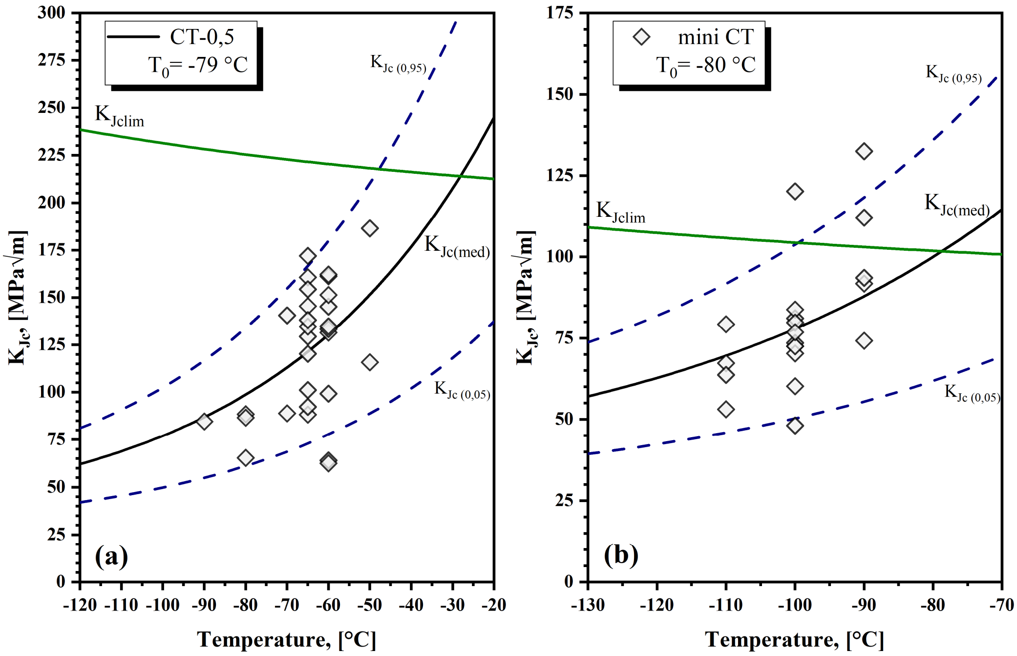

Figure 8. Temperature dependence for the fracture toughness, determined from the results of testing the CT-0,5 (a) and the mini CT (b) specimens of 15Kh2NMFA grade 1 steel

Table 4: Fracture toughness test results for 15Kh2NMFA grade 1 steel

Specimen type	T_0,°C	$\sum r_i \times n_i$	N	σ_{T0}, [°C]
CT-0,5	-79	4.83	29	5.2
mini-CT	-80	2.50	20	6.1

The Table 4 demonstrates that the ductile to brittle transition temperature (T_0) values obtained from tests with mini CT and CT-0.5 specimens differ only by 1 °C. This leads to a positive conclusion of using mini CT specimens to obtain the correct data on ductile to brittle transition temperature (T_0).

CONCLUSION

As part of the test for determination of ductile to brittle transition temperature, T_0, of SFVQ1A RPV steel provided by CRIEPI (Japan), NRC KI carried out research to determine the T_0 parameter based on the testing of mini CT specimens using the master curve method in accordance with ASTM E1921 Standard. The work was broken down into two phases. At Phase 1, the preprepared specimens were tested; at Phase 2, the specimens were prepared out of the bars 12×12×100 mm in size, with initial fatigue cracks' growing, their subsequent testing, and the results being processed.

Based on the analysis of the results obtained, it should be concluded that the T_0 parameters for the both groups of specimens coincide, considering the determination error. The results of the tests performed by NRC KI are well correlated with the test results obtained by Yamamoto et al. (2014).

The results were checked for agreement with the Weibull statistical distribution model used. Linear approximation of the points resulted in the values of coefficient n equal to 3.12 for the specimens prepared by CRIEPI, and to 4.04 for the specimens prepared by NRC KI. In case of combined processing of the both data sets, $n = 3.5$. The results fall within the evaluated parameter limits when the parameter is determined on a limited number of specimens. This allows for the conclusion that the experimental data obtained on mini CT specimens of SFVQ1A steel follow the Weibull statistical distribution, and the results of mini CT specimens' testing (along with the results obtained on CT-0.5 specimens in the works) demonstrated the correctness of the experimental data on fracture toughness, submitted by Wallin, K., (1984).

The positive experience of testing the specimens made of SFVQ1A RPV steel was carried over to the 15Kh2NMFA grade 1 steel. The results of using mini CT specimens of 15Kh2NMFA grade 1 steel in the initial state when compared to CT-0.5 specimens testing are demonstrated. The transition temperatures, T0, obtained from tests with mini CT and CT-0.5 specimens differ by 1 °C, which indicates the possibility of using mini CT specimens to obtain the correct data on fracture toughness.

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