



A modified correlation between K_{JIC} and Charpy V-notch impact energy of Chinese SA508-III steel at the upper shelf

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ABSTRACT

The fracture toughness plays a significant role in the structural integrity assessment of reactor pressure vessels (RPVs) in service temperature. The Charpy V-notch (CVN) impact test is used to estimate fracture toughness (K_{IC} or K_{JIC}) indirectly since universal fracture toughness tests are costly, sophisticated and frequently invalid. In this study, a modified correlation which based on the typical model of K_{JIC} -CVN at the upper shelf was established for Chinese SA508-III steel. Thereinto, the effect of test temperature (T) was directly considered in the correlation. To assess the accuracy of fracture toughness when calculating from the value of Charpy-V notch impact energy by using the modified correlation, both the Charpy-V notch impact tests and fracture toughness tests for Chinese SA508-III steel were conducted at different temperatures (100 °C, 150 °C, 200 °C, 250 °C and 320 °C). The results showed that the modified correlation exhibited the high precision for estimating fracture toughness of Chinese SA508-III steel and the relative error for tested and estimated results is within 8%, which is lower than that of other correlations.

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1. Introduction

Reactor pressure vessel (RPV) is a non-replaceable part in pressurized water reactors (PWRs), which operates under relatively high-temperature (320 °C) and high pressure, strong neutron irradiation [1–4]. Therefore, the structural integrity assessment of RPV has a significant effect on the security issues of nuclear power plants in service temperature.

Fracture toughness is the foremost mechanical property to assess the structural integrity of RPV. However, fracture toughness tests not only are costly and require very skilled manpower and special instrumentation, but also the obtained fracture toughness value is frequently invalid for high ductile materials [5–7], especially at the high temperatures [8–11]. Compared with the sophisticated fracture toughness tests [10,12,13], Charpy V-notch impact test [14] can be utilized to indirectly estimate the material fracture toughness for its low-costly, simplicity, wide familiarity and availability [15–17]. In general, the Charpy V-notch impact test

yields the energy to break the sample and the values of fracture toughness cannot be precisely obtained. It is necessary to establish a relationship between the values of Charpy V-notch (CVN) impact energy and fracture toughness, and a reliable correlation can be a useful tool for failure analysis and life prediction [18,19], especially for testing in high cost, high precision and high toughness materials, such as RPV steels.

In the past years, intensive efforts have been adopted for estimating the plane strain fracture toughness (K_{IC}) of various materials from their CVN values. Initially, Barsom and Rolfe [20] analyzed eleven kinds of high-strength steels and built a linear model of ($K_{IC}/R_{p0.2}$)² and (CVN/ $R_{p0.2}$). The similar model was also verified by Ault et al. [21] for ultra strength aircraft steel. Afterwards, this form was fitted in various suitable coefficients by many researchers [22–30] for different materials at the upper shelf, and some correlations have been adopted by ASME XI [16] and API 579 [17] standards. In addition to the above K_{IC} -CVN correlations which could estimate the fracture toughness from Charpy V-notch impact energy directly (defined as a direct method in this paper), some researchers [31–36] proposed a related power law type approximation of the J - R curve from the upper shelf CVN values. The correlation J - R curve is similar to the standard J - R curve in ASTM E1820 [5], then the fracture toughness (K_{JIC}) values could be calculated from this

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correlation J - R curve (defined as the indirect method). In this method, a lot of correction coefficients should be calculated by the upper shelf CVN values or test temperature and it is necessary to build the offset blunting line equation [5] to estimate the fracture toughness (K_{JIC}). Thus, it is relatively complicated when compared to the linear model of $(K_{JIC}/R_{P0.2})^2$ and $(CVN/R_{P0.2})$.

However, considering the difference of material compositions and properties, testing temperature and their application requirements, there is few researcher to verify the applicability of the above-developed empirical or semi-empirical correlations at relatively high temperature for Chinese RPV steel at present.

In this work, the Charpy V-notch impact energy and initiation fracture toughness of Chinese SA508-III steel at different temperatures (100 °C, 150 °C, 200 °C, 250 °C and 320 °C) were measured by Charpy-V notch impact test and J_{IC} test (resistance against crack initiation characterized by J -integral), respectively. For comparison, the valid J_{IC} was converted to K_{JIC} . Then, the applicability of some typical [20–26] and indirect [31–36] correlations with different forms at relatively high temperature for Chinese SA508-III steel was discussed. Based on the CVN and J_{IC} test results, a modified model between the values of fracture toughness (K_{JIC}) and CVN was proposed. Since there is almost no study focusing on the effect of temperature range on the direct K_{JIC} -CVN correlations from the upper shelf temperature (approximately 100 °C) to service temperature (320 °C) [19], the test temperature (T) was considered and introduced as a parameter in the proposed K_{JIC} -CVN correlation. The residuals of K_{JIC} between the measured values from the J_{IC} test (K_{JIC-T}) and the estimated values from the published and proposed K_{JIC} -CVN correlations were also investigated in detail.

2. Experimental procedure

2.1. Materials

Chinese SA508-III steel for RPV was used as the tested material and its chemical compositions are given in Table 1 (the remaining composition is Fe element). The chemical compositions of Chinese SA508-III steel are same with the ASTM steel of SA508 Gr.3 Cl.2 [37].

2.2. Uniaxial tensile test

The yield strength ($R_{P0.2}$), ultimate strength (R_m) and Young's modulus (E) of the Chinese SA508-III at 100 °C, 150 °C, 200 °C, 250 °C and 320 °C were determined by uniaxial tensile test with round bar specimen according to ASTM E8/E8M – 11 [38].

2.3. High-temperature Charpy impact testing

For the high-temperature Charpy impact testing, all Charpy specimens with a dimension of 10 mm × 10 mm × 55 mm were machined. The V-shaped notch radius is 0.25 ± 0.025 mm. The investigation was performed at 100 °C, 150 °C, 200 °C, 250 °C and 320 °C, respectively. An elevated temperature furnace was adopted to heat the Charpy specimens. Before testing, Charpy specimens and the tongs were heated up to the test temperatures and kept for 20 min. Subsequently, the tested specimen was quickly put into the holder of the CVN test machine and then the test control program was activated. An infrared thermometer which can read the

specimen temperature remotely was applied to record the temperature when the impact occurs. The impact velocity of testing of machine hammer was 5.3 m/s and the biggest impact energy of the striker was set as 300 J. The experimental data of impact energy was automatically calculated by using a control program on the impact test machine.

2.4. High-temperature J_{IC} testing

The Compact Tension (CT) specimen with a thickness of 25.00 mm was prepared with crack plane paralleling to axis direction of the RPV. After the fatigue pre-cracking of CT specimen, a final V-notch side groove depth of 10% thickness at each side of the specimen was manufactured. The parameters and photograph of the specimen are shown in Fig. 1.

All the fracture toughness tests were conducted for the specimens under displacement loading control by a testing machine INSTRON 8850 with a high temperature furnace, as shown in Fig. 2. The displacement rate was set at 1 mm/min. Load P and the load line displacement were obtained from the testing machine.

Fracture toughness tests were conducted in a high temperature furnace at 100 °C, 150 °C, 200 °C, 250 °C and 320 °C, respectively. Three K-type-thermocouples in contacting with the specimen at the upper side, middle side, downside were used to measure the temperature, respectively. Before running tests, the time for temperature homogenization of all specimens was no less than 30 min. The temperature error was controlled within ± 3 °C during the test.

The J -integral and crack length were calculated by the unloading compliance method which was the strongest recommendation in the ASTM E1820 [5]. In this method, a displacement gauge clipped into the knife edges was required to measure the load line displacement (LLD). A high temperature Crack Opening Displacement (COD) gauge was adopted to measure the displacement of the specimen directly on the specimen and the measured method can be found in the ASTM E1820 [5]. In general, the COD seat was installed on the high temperature furnace. However, during the test, the vibration of the testing machine (INSTRON 8850) often leads to the furnace instability, which will reduce the test precision of crack length. Thus, a seat and a rack of COD gauge were designed to absorb vibration and improve the test precision. The seat of COD was fixed in the rack of COD, and the rack of COD was fixed at the base of the testing machine (INSTRON 8850) as shown in Fig. 2.

3. Results and discussion

3.1. CVN and K_{JIC} values for Chinese SA508-III steel

In order to describe the results clearly, various values of $R_{P0.2}$, E , CVN and K_{JIC} against test temperature were compiled and the results are shown in Fig. 3. For each type of test, three specimens were tested for the average at each test temperature. 300 J Charpy impact test machine was used for high temperature CVN tests and when the absorption energy exceeding 240 J was invalid [14] and be eliminated in Fig. 3. In the ASTM E1820-15 [5], if all the qualifications are valid and the qualified J_{IC} can be converted to K_{JIC} by Eq. (1). In this paper, the obtained J_{IC} values are valid, therefore, the J_{IC} was transformed to K_{JIC} .

Table 1
Chemical compositions of Chinese SA508-III steel (wt %).

Element	C	Si	Mn	Ni	Cr	Mo	P	S	Cu	V
Content	0.240	0.081	1.350	0.820	0.160	0.510	0.008	≤ 0.001	0.017	0.003

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