Reliability research of reference temperature estimation of RPV materials using Charpy impact energy

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Abstract

The standard fracture toughness test is usually limited in practical engineering projects due to the expensive and sophisticated experimental procedure or limited specimens. The traditional method to evaluate the structural integrity is to estimate the ductile–brittle transition region by Charpy tests. However, this fuzzy estimation is sometimes too conservative and cannot obtain quantitative fracture toughness data. In recent years, many achievements have been made in the study of the relations between Charpy impact test and fracture toughness test. Although acceptable, the errors caused by these formulas are rarely compared in detail formulas with stable deviation will be more suitable for research or engineering application. Therefore, this paper compares the data of four different ferritic steels to test the error stability of each formula, so as to provide reference for experimental research and engineering facilities. The reliability of each correlation is checked from the view of accuracy or appropriate conservatism. In this research, We found that the $T_{28J}-T_0$ correlations, the empirical formula proposed by Rolfe, Novak and Barsom (abbreviated as RNB) and the Mean-4 Procedure obtained by IGC-parameter give the reference temperatures more accurately or appropriately conservatively. These formulas should be preferred in practical application.

Keywords Charpy impact test · Empirical formula · Reference temperature · RPV materials · IGC-parameter

1 Introduction

Ferritic steels have obvious ductile–brittle transition behavior. The fracture mode is brittle fracture when the temperature is lower than a certain range and is ductile fracture when the temperature is higher than that range. Within this range, the fracture mode gradually transits from brittle fracture to ductile fracture with the increase of temperature. This temperature range is named as the ductile–brittle transition region. Ferritic steels hardly undergo plastic deformation before the brittle fracture occurs. Therefore, brittle fracture is instantaneous and difficult to prevent. Moreover, the unstable propagation of crack hardly requires external force. Consequence is

expected to be very serious once brittle fracture occurs. To avoid brittle fracture of ferritic steels, the lower working temperature limit must be higher than the transition region. Under long-term irradiation, the transition region will move toward higher temperature due to the neutron irradiation embrittlement [1]. To ensure the structural integrity and service life of reactor pressure vessels, precise fracture-safe analysis is very important and necessary.

Master Curve method is a widely used technique to research and analyze fracture toughness. This method characterizes the distribution of fracture toughness in transition region as a curve determined by the reference temperature. The lower bound of fracture toughness is given by measuring and calculating the reference

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temperature. ASTM E1921 provides methods to determine the reference temperature, including a single-temperature method and a multi-temperature method [2]. However, fracture toughness test is complex and expensive because of the requirements of stringent procedures, specialized testers and thick specimens with sharp fatigue pre-crack [3]. In addition, limited specimens provided by nuclear facilities may not meet the requirement of fracture toughness test. One of the ways to solve this problem is to use small size samples. But the size effect makes the measured fracture toughness deviate from the normal value [4]. Therefore, the methods by transforming a non-SSY value of K_{JC} to an equivalent SSY value have been researched in recent years [5]. But without appropriate official standards, these studies cannot be applied to practical projects yet.

The structural integrity evaluation of important facilities is often based on the experimental results of small samples, such as fracture toughness test, Charpy impact test, small punch test, etc. [6, 7]. Charpy impact test is a traditional test used to determine the notch sensitivity of metal materials. Compared with the standard fracture toughness test prescribed by ASTM, Charpy impact test has lower requirements for sample preparation and equipment. The sensitivity to material quality, defects and structure is also not available in static load test. In addition, Charpy impact test requires fewer specimens. Fractured Charpy impact specimens can be reconstituted and reused [8, 9]. This technology makes it possible to obtain more test data with a small number of specimens. However, the test data obtained from Charpy impact test (mainly impact energy) cannot directly represent the fracture toughness or reference temperature. Sometimes, determining the temperature shift by the impact test is too conservative. The differences of specimen size and strain rate effect [10] between Charpy impact test and fracture toughness test also complicate the relationship between impact energy and fracture toughness.

In the past few decades, Charpy impact test was the main way to evaluate RPV materials and a large number of impact test data have been accumulated. Many correlations between impact energy and fracture toughness have been established, such as formulas for estimating the reference temperature directly with 28 J or 41 J impact energy proposed by Sattari-Far and Wallin [11], or the empirical formula for estimating fracture toughness with the impact energy established by Rolfe, Novak and Barsom, etc. [12, 13]. Nowadays, with the development of computer technology, finite element analysis (FEA) has been applied increasingly to crack simulation and the prediction of fracture toughness [14–16]. The finite element method also makes it possible to obtain fracture toughness data by tensile test. [17] It greatly simplifies the acquisition of fracture toughness data. But the finite

element analysis cannot be applied to practical engineering project yet. Charpy impact test is still the main way to determine the ductile brittle transition temperature (DBTT). These Charpy-fracture toughness formulas have been established and tested for many years. They all have inevitable errors. Although recognized, there is not much work to study and compare these errors. If these formulas need to be applied to practical projects, it will be very helpful to know the degree of their errors. An empirical formula with stable error is of great significance to both practical engineering and academic research.

In this paper, several different formulas are applied to four RPV materials. The calculated results are compared with the results of the standard fracture toughness test and their deviations are compared. The comparison results will be discussed from the view of magnitude and stability of the deviation, as well as the complexity of the calculation process. The purpose of this paper is to find out the most suitable fracture toughness estimation formula for ferritic steels, and to provide reference for practical engineering and academic research.

2 Relations between reference temperature and Charpy impact energy

2.1 Relations between reference temperature and T_{28J} or T_{41J}

28 J and 41 J Charpy energy temperature are often used to define DBTT (ductile brittle transition temperature). They can also be used to estimate the reference temperature. Some simple formulas for estimating reference temperature are shown in Table 1.

Wallin proposed the relations between reference temperature and T_{28J} or T_{41J} (i.e. Equations (2) and (4), and the corresponding conservative formulas (i.e. Eqs. (2a) and (4a)) in [11]. The relation between T_{28J} and reference temperature is also written as Eq. (1) in [18]. Equations (1) is close to Eq. (2), and only Eq. (1) with smaller standard

Table 1 Relations between reference temperature and T_{28J} or T_{41J}

Formulas	Eq. nos.
$T_0 = T_{28J} - 18 (\sigma = 15^\circ\text{C})$	(1)
$T_0 = T_{28J} - 19 (\sigma = 22^\circ\text{C})$	(2)
$T_{0-1\sigma} = T_{28J} + 3$	(2a)
$T_0 = 1.09 \cdot T_{28J} - 11.2 (\sigma = 18^\circ\text{C})$	(3)
$T_{0-1\sigma} = 1.18 \cdot T_{28J} - 12.52$	(3a)
$T_0 = T_{41J} - 26 (\sigma = 25^\circ\text{C})$	(4)
$T_{0-1\sigma} = T_{41J} - 1$	(4a)

All the temperatures in this table are in $^\circ\text{C}$

deviation is usually considered. Equations (3–3a) are other formulas between T_{28J} and reference temperature provided by Sreenivasan [19]. These formulas will be used in this paper as well. In [19], the non-linear correlations between reference temperature and T_{28J} or T_{41J} are also studied. The corresponding non-linear formulas are developed as shown in Eqs. (11–12) in Table 3.

2.2 One-step or two-step empirical formulas

Similar to the ductile–brittle transition curve, the Charpy transition curve can also be divided into three regions: upper shelf, transition region and lower shelf. Empirical formulas cannot describe all three regions at the same time because of the complexity of the Charpy transition curve. Empirical formulas are only applicable to one or two of the three regions. In this paper, only empirical formulas applicable to transition region are discussed.

Some commonly used one-step or two-step empirical methods applicable to transition region are shown in Table 2. In Table 2, K_{IC} or K_D is the Static or dynamic fracture toughness in $\text{MPa}\sqrt{\text{m}}$ and C_V is the Charpy impact energy in J. σ_{ys-RT} is the yield strength at room temperature in MPa and E is Young modulus in GPa. The corresponding fracture toughness transition curves can be obtained by applying these empirical formulas (i.e. Eqs. (5–9)) once the Charpy transition curves are available. Usually, the temperature corresponding to a fracture toughness of $100 \text{ MPa}\sqrt{\text{m}}$ will be used as an estimation of the reference temperature. To distinguish the estimated results conveniently, the reference temperatures calculated by this method are recorded as T_{K100-X} . X is the initials of the sources of the empirical formulas. Therefore, the four empirical formulas are abbreviated as RNB [12, 13], SC [20], RLB [21] and BR [12]. The estimated reference temperatures of Eqs. (5–9) obtained by this method are $T_{K100-RNB}$, $T_{K100-SC}$, $T_{K100-RLB}$, $T_{K100-BRKD}$ (calculated by Eq. (8) alone) and $T_{K100-BRS}$ (calculated by Eqs. (8–9)) respectively.

Strictly speaking, the fracture toughness represented by T_{K100-X} represents the fracture toughness of specimens

Table 3 Non-linear fitting formulas for reference temperature

Formulas	Eq. nos.
$T_{Q-28} = -222.55 + 217.64 \cdot \exp(0.0062 \cdot T_{28J})$	(11)
$T_{Q-41} = -275.28 + 252.19 \cdot \exp(0.00463 \cdot T_{41J})$	(12)
$T_{Q-RNB} = (-14.25 + T_{K100-RNB}) / (0.8166 - 0.0019 \cdot T_{K100-RNB})$	(13)
$T_{Q-SC} = (-25.67 + T_{K100-SC}) / (0.8713 - 0.0019 \cdot T_{K100-SC})$	(14)
$T_{Q-RLB} = (-29.3 + T_{K100-RLB}) / (0.8987 - 0.0018 \cdot T_{K100-RLB})$	(15)
$T_{Q-IGC1} = (-55.33 + P_{IGC1}) / (2.42 - 0.0028 \cdot P_{IGC1})$	(16)
$T_{Q-IGC2} = (-21.578 + P_{IGC2}) / (0.8498 - 0.0033 \cdot P_{IGC2})$	(17)

All the temperatures in this table are in °C

with thickness of 10 mm. Because of the lower thickness, the calculated fracture toughness is higher than the actual one and the corresponding reference temperature is lower as well. The fracture toughness values of different thickness can be normalized to those of 1T thickness by Eq. (10). Thickness effect is not negligible. Omitting thickness normalization simplifies the calculation process. But it is still necessary to discuss the influence. The 1T-equivalent fracture toughness (K_{IC}) transition curve can be calculated by using Eq. (10). For convenience of distinction, the temperature corresponding to 1T-equivalent fracture toughness of $100 \text{ MPa}\sqrt{\text{m}}$ is recorded as $T_{K100-X(1T)}$. The subscript (1T) indicates that the equivalent thickness is 1T.

$$K_{IC(1T)} = 20 + (K_{IC} - 20) \cdot \left(\frac{B}{B_0}\right)^{1/4} \quad (10)$$

B is 10 mm and B_0 is 25.4 mm for standard Charpy impact specimens.

Omitting thickness normalization may enlarge the error. The non-linear fitting formulas between T_{K100-X} and T_0 proposed in [19] may be helpful for error reduction. As shown in Eqs. (13–15) in Table 3, the reference temperatures calculated by using the fitting formulas are termed

Table 2 One-step or two-step empirical formulas

Sources	Formulas	Suitable Range		Eq. nos.
		$C_V(\text{J})$	$\sigma_{ys-RT}(\text{MPa})$	
Rolfe, Novak and Barsom	$K_{IC} = (E \cdot 1000 \cdot (2.28) \cdot 10^{-4} \cdot C_V^{1.5})^{0.5}$	4–82	270–1700	(5)
Sailors and Corten	$K_{IC} = 14.63 \cdot C_V^{0.5}$	7–68	410–480	(6)
Robert's lower-bound correlation	$K_{IC} = 8.47 \cdot C_V^{0.63}$	–	–	(7)
Barsom and Rolfe	$K_D = (0.64 \cdot E \cdot C_V)^{0.5}$	2.7–61	250–345	(8)
	$T_{shifted} = T_{CVN} - (119 - 0.12 \cdot \sigma_{ys-RT})$			(9)

Where K_{IC} or K_D is the Static or dynamic fracture toughness in $\text{MPa}\sqrt{\text{m}}$ and C_V is the Charpy impact energy in J. σ_{ys-RT} is the yield strength at room temperature in MPa and E is Young modulus in GPa

as T_{Q-X} , and subscript X represents the initials of empirical formulas as well.

2.3 Relations between reference temperature and IGC-parameter

Based on Miyata and Tagawa's research [22] about the relations between micro-cleavage fracture stress (σ_f , a given steel constant), yield stress and fracture toughness, Sreenivasan defined two new parameters, P_{IGC1} and P_{IGC2} [19], as follows:

$$P_{IGC1} = \left(\frac{\sigma_f}{\sigma_{ys-RT}} \right) \cdot T_{41J} \quad (18)$$

$$P_{IGC2} = \left(\frac{\sigma_{ys-T41}}{\sigma_{ys-RT}} \right) \cdot T_{41J} \quad (19)$$

where T_{41J} is the 41 J Charpy energy temperature and σ_{ys-T41} is the yield strength at T_{41J} . σ_{ys-RT} is the yield strength at room temperature. According to Miyata and Tagawa's research, σ_f can be estimated using $K_{IC} - \sigma_{ys}$ or $K_{Id} - \sigma_{yd}$ data at very low temperature (about -150°C) by solving the following Eq. (20) [19].

$$0 = \left(\frac{K_{IC-T1}}{K_{IC-T2}} \right) - \left(\frac{\sigma_{ys-T1}}{\sigma_{ys-T2}} \right) \frac{\sqrt{\exp\left(\frac{\sigma_f}{\sigma_{ys-T1}} - 1\right) - 1}}{\sqrt{\exp\left(\frac{\sigma_f}{\sigma_{ys-T2}} - 1\right) - 1}} \quad (20)$$

where $K_{IC} - \sigma_{ys}$ values at two temperatures are used. If there is sufficient data, multiple groups of σ_f can be obtained with the temperature interval of $10\text{--}15^\circ\text{C}$. The mean value is taken if σ_f values agree within 10% [19]. P_{IGC1} and P_{IGC2} can be used to estimate the reference temperatures with Eq. (16–17) [19] and the calculated results are expressed as T_{Q-IGC1} and T_{Q-IGC2} respectively.

3 Materials and experimental data

3.1 Stress–strain relations of the materials

Four commonly used RPV materials are investigated in this paper. The grades are China A508-3, USA A533B, Euro 20MnMoNi55 and 16MnDR and the chemical compositions of these materials [23, 24] are listed in Tables 4 and 5.

Tensile test is widely used to measure the mechanical properties of materials, such as Young modulus, yield strength, etc. These data are also necessary to evaluate the structural integrity. To obtain the mechanical properties of 16MnDR, the tensile test was carried out in this paper. Specimens were prepared according to GB/T 2975-1998 [25]. The test was carried out on CMT5105 computer controlled electronic universal testing machine. Before the test start, the specimen was kept at the target temperature for at least 100 min to ensure the uniformity of the temperature. The test temperature ranged from -100°C to room temperature and the loading rate was 2 mm/min. The specimen size and experimental data used in this paper are shown in Figs. 1 and 2.

The yield strength data of 16MnDR and the rest three materials [26] are fitted and shown in Eqs. (21–24) respectively:

$$\text{A508-3: } \sigma_{ys}(\text{MPa}) = 0.0013 \cdot T^2 - 0.6171 \cdot T + 462.58 \quad (21)$$

$$\text{A533B: } \sigma_{ys}(\text{MPa}) = 0.0074 \cdot T^2 - 0.2386 \cdot T + 493.1278 \quad (22)$$

$$\text{20MnMoNi55: } \sigma_{ys}(\text{MPa}) = 0.0112 \cdot T^2 - 0.0431 \cdot T + 494.01 \quad (23)$$

$$\text{16MnDR: } \sigma_{ys}(\text{MPa}) = 380.41 - 0.6633 \cdot T \quad (24)$$

where σ_{ys} is yield strength in MPa and T is in $^\circ\text{C}$.

Table 4 Chemical composition of three materials/ %

Material Brand	Chemical Composition									
	C	Si	Mn	Ni	Cr	Mo	P	S	Cu	V
A533B	≤ 0.25	0.15–0.40	1.15–1.50	0.40–0.70	–	0.45–0.60	≤ 0.035	≤ 0.035	≤ 0.10	≤ 0.05
20MnMoNi55	0.17–0.23	0.15–0.30	1.20–1.50	0.50–1.00	≤ 0.20	0.40–0.60	≤ 0.012	≤ 0.015	≤ 0.10	≤ 0.02
China A508-3	0.16–0.20	0.10–0.30	1.20–1.55	0.50–0.80	≤ 0.20	0.45–0.55	≤ 0.008	≤ 0.008	≤ 0.08	≤ 0.01

Table 5 Chemical composition of 16MnDR/ %

Material Brand	Chemical Composition					
	C	Si	Mn	Al _t	P	S
16MnDR	≤ 0.20	0.15–0.50	1.20–1.60	≥ 0.02	≤ 0.025	≤ 0.012

Fig. 1 16MnDR: Sample size of tensile test **Fig. 2** 16MnDR: Fitting curve of yield strength

3.2 Charpy impact data of the materials

Charpy impact test is a Commonly used test to check the dynamic mechanical properties of materials. It measures the absorbed energy when a pendulum breaks a sample of a certain shape. Although not very precisely, the Charpy impact energy can be used to determine the transition region conveniently as the basis for evaluating the service life and security of RPV. In lower shelf and upper shelf, the fracture modes of ferritic steels are mainly brittle fracture and ductile fracture respectively with relatively stable values of Charpy impact energy. In transition region, the fracture mode gradually changes from brittle fracture to ductile fracture with the increase of temperature. The impact energy data are also more dispersed. According to Oldfield's research [27], the Charpy impact energy data can be fitted into a tangent hyperbolic function.

The Charpy impact test of 16MnDR was performed under the guidance of the standard GB/T 229-2007 [28]. Standard impact specimens of 10 mm*10 mm size were prepared

Fig. 3 16MnDR: Sample size of Charpy impact test

according to GB/T 2975-1998 [25]. The detailed geometric size of the specimen is shown in Fig. 3. V-shaped notch with depth of 2 mm was processed in the middle of the specimen. The impact test was conducted in the JBD-300A low temperature impact tester. The radius of the pendulum blade was 2 mm. In the experiment, the pendulum had about 5 m/s loading velocity and 300 J impact energy. The experimental temperature ranged from -100 to -20 °C and the test temperatures were maintained with liquid nitrogen and anhydrous ethanol solution. As shown in Fig. 4, the impact data are fitted into a tangent hyperbolic curve.

The Charpy transition curves for 16MnDR and the rest three materials [26] are shown in Eqs. (25–28) respectively.

$$A508-3: E_{CVN} = 130.89 + 123.22 \cdot \tanh\left(\frac{T + 17.00}{28.10}\right) \quad (25)$$

$$A533B: E_{CVN} = 113.68 + 90.36 \cdot \tanh\left(\frac{T + 4.81}{21.88}\right) \quad (26)$$

Fig. 4 16MnDR: The Charpy transition curve

$$20\text{MnMoNi55}: E_{CVN} = 117.07 + 88.00 \cdot \tanh\left(\frac{T + 48.40}{29.36}\right) \quad (27)$$

$$16\text{MnDR}: E_{CVN} = 81.12 + 114.05 \cdot \tanh\left(\frac{T + 80.4}{20.65}\right) \quad (28)$$

where E_{CVN} is the Charpy impact energy in J and T is in °C. The Charpy transition curves will be used to estimate the reference temperature in the following research.

3.3 Young modulus of the materials

In the process of calculation, the influence of temperature on Young modulus should be taken into account. The relationship between Young modulus and temperature commonly used in ferritic steels is provided in [29], as shown in Eq. 29.

$$E = 207.2 - 0.0571 \cdot T(^{\circ}\text{C}, \text{GPa}) \quad (29)$$

4 Results and discussion

4.1 Estimations of reference temperature by directly use of T_{28J} or T_{41J}

In this section, the relations between T_0 and T_{28J} or T_{41J} shown in Eqs. (1–4a) are mainly researched and compared. T_{28J} and T_{41J} are obtained directly by the Charpy transition curves. The estimated results are recorded as $T_{0(1)}$, $T_{0(2a)}$, $T_{0(3)}$, $T_{0(3a)}$, $T_{0(4)}$ and $T_{0(4a)}$ with subscript denoting the serial numbers of the corresponding formulas respectively. The reference temperatures calculated by Eqs. (11–12) are recorded as T_{Q-28} and T_{Q-41} respectively. In this paper, the deviations (expressed in ΔT_0 and equal to estimated

Fig. 5 Deviations of reference temperatures estimated by T_{28J} or T_{41J}

temperature minus tested temperature) between the estimated temperatures and tested temperatures are compared. All the deviations are plotted in Fig. 5 with dashed lines representing the deviation of $\pm 15^{\circ}\text{C}$.

According to the relevant literature [24], the tested T_0 of 16MnDR obtained by the fracture toughness test is -102°C . Reference temperatures of China A508-3 and USA A533B are considered as -63°C and -58°C [26] respectively. Reference temperature of Euro 20MnMoNi55 is between -120 and -130°C [26] and the median value -125°C is used for calculation and comparison in this paper.

According to the data in Fig. 5, most of the deviations fluctuate within certain ranges. Those stable trends reveals that there is a relatively stable relationship between T_0 and T_{28J} or T_{41J} . In Fig. 5, the results calculated by T_{28J} ($T_{0(1)}$ to $T_{0(3a)}$) and T_{Q-28} obviously have smaller fluctuation ranges than that calculated by T_{41J} . This trend indicates that T_{28J} can reflect the reference temperatures more accurately than T_{41J} . However, some materials can hardly obtain 28 J impact energy because mostly the T_{28J} falls on the lower shelf. The formulas of T_{28J} cannot be applied to all materials.

By comparing the estimated results of each formula, T_{Q-28} and $T_{0(2a)}$ are noticed to have the smallest deviation amplitude. This phenomenon makes them the preferred choices for simple prediction of reference temperature. The former can provide an accurate prediction while the latter is relatively conservative. The data of Charpy impact test have a wide range of dispersion, especially in transition region. The reference temperatures estimated by Charpy impact tests have greater error than that estimated by fracture toughness tests. In addition, the research of fracture toughness by samples is affected by

some uncertainties [30]. For safety reasons, the estimated reference temperatures selected in practical engineering should tend to be appropriately conservative. Therefore, the latter one is preferred for practical engineering projects. But these two formulas are not suitable for all situations. Neither T_{Q-28} nor $T_{0(2a)}$ can be obtained for materials that cannot obtain the T_{28J} temperature. In that case, although the errors are slightly larger, conservative $T_{0(4a)}$ and relatively accurate T_{Q-41} can also be used as backup options.

4.2 Estimations of reference temperature by empirical formulas

This section is devoted to discussing the estimation trends of several empirical formulas. The estimated results of each empirical formula are plotted in a single graph, as shown in Figs. 7, 8, 9 and 10 respectively. The T_{K100-X} , $T_{K100-X(1T)}$ and T_{Q-X} mentioned above can be calculated directly by combining the Charpy transition curves with empirical formulas and the fitting formulas in Table 3.

The multi-temperature formula in Eq. (30) requires several fracture toughness at different temperatures. These fracture toughness data can be obtained by various empirical formulas. The multi-temperature formula is used to calculate the reference temperature in master curve method. At least six pairs of valid fracture toughness data and the corresponding temperatures are required. The Charpy transition curve, empirical formula and the thickness normalization shown as Eq. (10) can be combined into the fracture toughness—temperature relation of specimens with equivalent thickness of 1T. The data used in multi-temperature method are taken from here and recorded as $K_{IC(1T)}$. Data can be selected in the range of $50 \text{ MPa}\sqrt{\text{m}} \leq K_{IC(1T)} \leq 150 \text{ MPa}\sqrt{\text{m}}$ [26]. The selection

Fig. 6 Transition threshold of 16MnDR

Fig. 7 Deviations of reference temperatures estimated by RNB

of these data must meet the requirements of the multi-temperature formula.

The empirical formula applicable to transition region is usually not considered to be applicable to the upper shelf. Therefore, the selected data should not be affected by the impact energy of the upper shelf. The threshold of fracture toughness data can be set according to the Ref. [31]. Taking the 16MnDR transition curve in Fig. 6 as an example, an eye-fit straight line (the dotted line in Fig. 6) is drawn from the middle of the impact energy curve. The trend of separating the straight line from the impact energy curve starts at the position with about 140 J impact energy. Thus, the impact energy of the upper shelf must be higher than 140 J. The 140 J can be used as the threshold of transition region. When selecting fracture toughness data, the corresponding impact energy should not exceed 140 J.

Fig. 8 Deviations of reference temperatures estimated by SC

Fig. 9 Deviations of reference temperatures estimated by RLB

Fig. 10 Deviations of reference temperatures estimated by BR

After determining the range of data selection, an appropriate number of $K_{IC(1T)}$ data on the temperature axis will be equidistantly selected and the corresponding reference temperature will be calculated by solving Eq. (30). Their results are recorded as $T_{Q-X(mul)}$.

$$0 = \sum_{i=1}^{i=n} \frac{\delta_i \cdot \exp \{0.019(T_i - T_0)\}}{[31 - K_{\min} + 77 \exp \{0.019(T_i - T_0)\}]} - \sum_{i=1}^{i=n} \frac{(K_{Jd} - K_{\min})^4 \cdot \exp \{0.019(T_i - T_0)\}}{[31 - K_{\min} + 77 \exp \{0.019(T_i - T_0)\}]^5} \quad (30)$$

where $K_{\min}$ is 20 MPa $\sqrt{m}$. Kronecker delta δ_i is 1 for valid data and 0 for invalid data.

The validity of the calculated $T_{Q-X(mul)}$ are judged according to ASTM E1921.

After completing all the calculation, the deviations of the estimated values are compared. As shown in Figs. 7, 8, 9 and 10, for empirical formulas except BR, all the T_{Q-X} values float around the measured values. Except Euro 20MnMoNi55, the errors within $\pm 10^\circ\text{C}$ can be maintained for any other materials. As for 20MnMoNi55, it seems that all estimates of its reference temperature tend to be conservative. Although T_{Q-X} behaves a little conservatively for 20MnMoNi55, T_{Q-X} still outperform other predictions. By comparing T_{K100-X} with $T_{K100-X(1T)}$, it is noticed that the calculated T_{K100-X} still keeps a certain degree of conservatism. Omitting thickness normalization reduces the fluctuation range of the estimated values by almost one third, making the deviation more stable, and greatly simplifying the calculation process. So T_{K100-X} is more suitable for use. $T_{Q-X(mul)}$ is calculated by the fracture toughness of 1T equivalent thickness and the multi-temperature method. Compared with $T_{K100-X(1T)}$, the results of $T_{Q-X(mul)}$ are always slightly higher by nearly 5°C . The involvement of multi-temperature method slightly enhances the conservativeness of empirical formulas. However, empirical formulas are conservative enough. This enhancement makes the results of $T_{Q-X(mul)}$ overly conservative and may affect the correct evaluation of structural integrity. In addition, $T_{Q-X(mul)}$ uses the multi-temperature method combined with empirical formulas and the calculation process is relatively complex. Considering practicality, $T_{Q-X(mul)}$ is not priority for the estimation of reference temperature.

The empirical formulas are compared with each other in this paper. As can be seen in Fig. 10, the estimated results of the two-step empirical formula tend to be on the low side and the estimations of 16MnDR deviate greatly from the tested value. The two-step empirical formula is the first one that should be excluded from selection due to the unstable deviations. Then comparing the one-step empirical formulas in Fig. 7, 8 and 9, it can be seen that these three one-step empirical formulas show similar trends. Obviously, RNB empirical formula is more stable since the deviations are about one quarter smaller than other empirical formulas. Based on Fig. 7 and the conclusion drawn in the previous paragraph, it can be concluded that the estimations of T_{Q-RNB} and $T_{K100-RNB}$ are the most reliable. The former can provide relatively accurate estimation and the latter can be applied to practical projects with proper conservatism. Both of them are preferred for estimating reference temperature.

4.3 Estimations of reference temperature by IGC-parameter

σ_f must be known for the calculation of P_{IGC1} . According to the Ref. [26], σ_f of A533B and 20MnMoNi55 can be defined as 2148 MPa and 2199 MPa. For A508-3, due to the lack of sufficient fracture toughness data near -150°C [26], σ_f is not available and P_{IGC1} is also not considered in this paper. The minimum test temperature of 16MnDR also does not reach -150°C [24]. The lowest test temperature is -100°C . Calculation shows it is impossible to obtain a stable and reliable σ_f by using these data because of the widely distribution of fracture toughness data at this temperature. So similarly, the P_{IGC1} of 16MnDR is also not considered in the following comparisons.

P_{IGC1} and P_{IGC2} can be calculated by the Charpy impact energy curves and yield strength formulas of the four materials. The parameters P_{IGC1} and P_{IGC2} are used in Eqs. (16–17). The calculated reference temperatures are termed as T_{Q-IGC1} and T_{Q-IGC2} respectively and the subscripts indicate that the estimated values are calculated by using IGC parameters. According to the Ref. [19], T_{Q-28} , T_{Q-41} , T_{Q-IGC1} and T_{Q-IGC2} have a tendency to compensate each other. The mean value of the four data can be closer to the tested value. The mean value is recorded as T_{Q-M4} . If one of the four value is not available, the mean value can also be recorded as T_{Q-M3} . For convenience, T_{Q-M3} and T_{Q-M4} are denoted by $T_{Q-M3/M4}$. $T_{Q-M3/M4}$ will be used as the estimation of reference temperature and compared with experimental value.

This procedure using the mean value as reference temperature is named as the Mean-4 Procedure [19]. To make a significant comparison between T_{Q-28} , T_{Q-41} , T_{Q-IGC1} , T_{Q-IGC2} and their mean value $T_{Q-M3/M4}$, these estimations are plotted in the same graph, as shown in Fig. 11.

T_{41J} is easily obtained and T_{Q-IGC2} is available for most materials. Comparing against other estimated values, the T_{Q-IGC2} values show high degree of accuracy for the first three materials. However, T_{Q-IGC2} behaves a little conservatively for 20MnMoNi55 and shares similar trend with the estimated results of empirical formulas. As for T_{Q-IGC1} , due to the lack of sufficient data, only the T_{Q-IGC1} values of two materials can be calculated. Therefore, the existing data cannot show the trend of deviation, and cannot prove that T_{Q-IGC1} has enough reliability. For $T_{Q-M3/M4}$, it is obvious that the deviations are less than 5°C for the first three materials. The deviation of 20MnMoNi55 is larger than that of other materials. However, the degree of conservatism was decreased and the deviation is reduced to about 8°C . Generally speaking, the $T_{Q-M3/M4}$ values show great agreement with the tested T_0 . In terms of the universality of application, $T_{Q-M3/M4}$ can be obtained for all the four materials and the lack or excessive deviation of one component has

Fig. 11 Deviations of reference temperatures estimated by IGC-parameter

limited influence on the mean value. In conclusion, compared with other estimations of IGC parameters, the mean value, $T_{Q-M3/M4}$, was recommended to be a preferred choice for predicting accurate reference temperature.

5 Conclusions

In this paper, several methods for estimating reference temperature are researched. Data of four commonly used RPV ferritic steels are applied to estimate the reference temperatures. The reliability of these methods is tested by comparing the test values with the estimated values, so as to find the most suitable estimation methods for practical engineering. The conclusions are as follows:

1. T_{28J} has a more stable relationship with reference temperatures than T_{41J} , and also can be used to obtain more reliable predictions. T_{Q-28} and $T_{0(2a)}$ calculated by T_{28J} can be used as the preferential choice. The former is relatively accurate and the latter is suitable for conservative practical engineering projects. Despite the large deviations, conservative $T_{0(4a)}$ and accurate T_{Q-41} calculated by T_{41J} can also be used as backup options for materials without T_{28J} .
2. Generally speaking, one-step empirical formulas are more accurate and reliable than two-step empirical formula. For one-step empirical formulas, RNB empirical formula is preferred because of the smaller and more stable deviation. Empirical formulas are sufficiently conservative. However, thickness normalization and combination with the multi-temperature method will improve the conservativeness of empirical

formulas. Both of them are not preferred because of excessive conservatism. T_{Q-RNB} calculated by empirical formula and non-linear fitting formula gives accurate estimations and $T_{K100-RNB}$ calculated directly by empirical formula can maintain appropriate conservatism. Both of them are preferential choices for ferritic steel.

3. $T_{Q-M3/M4}$, the mean value of T_{Q-28} , T_{Q-41} , T_{Q-IGC1} , T_{Q-IGC2} , has a wide range of applications and relatively accurate accuracy. The process of calculating mean values weakens the degree of deviation and the requirement for materials. This feature turns $T_{Q-M3/M4}$ into another reliable choice to obtain accurate reference temperature.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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