Specimen size effect on the ductile-brittle transition reference temperature of A508-3 steel

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ARTICLE INFO

Keywords:

Reactor pressure vessel steel
Fracture toughness
Ductile-brittle transition reference temperature
Size effect
J-Q theory

ABSTRACT

Fracture toughness is a key parameter for evaluating the structural integrity of reactor pressure vessels (RPV). In this paper, fracture toughness K_{Jc} of different sized RPV specimens is tested at different temperatures. Master Curve method was used to model K_{Jc} and the ductile-brittle transition reference temperature T_0 is obtained. It is shown that the smaller the specimen size is, the lower the T_0 value is. The small specimen is not able to completely replace the standard 1CT specimen in the irradiation surveillance program to obtain T_0 and material toughness. J-Q theory is employed to study size effect and crack tip constraint effect on K_{Jc} . It is shown that Q (constraint) decreases as the specimen size decreases. A prediction model to transfer the reference temperature T_0 of different specimens is developed considering constraint effect by means of Q.

1. Introduction

Reactor pressure vessel (RPV) is a key component in nuclear power plants that cannot be replaced. During the operation service, RPV materials subject to neutron embrittlement and hardening [1]. This leads to a change in the fracture behavior of the material, which in turn affects its service life and safety. Since the RPV material is ferritic steel, it is a body-centered cubic structure, which itself has the characteristics of brittleness. This means that the Charpy-impact work of the material decreases significantly at low temperatures, and the transition from ductile to brittle fracture occurs. Correspondingly, the fracture microscopic mechanism of changes from dimple fracture to cleavage fracture in the ductile-brittle transition temperature range [2–4]. A small temperature variation will cause a large variation in fracture toughness K_{Jc} . Even at the same temperature, the obtained K_{Jc} is very scattered, which makes the characterization of K_{Jc} quite difficult. With the development of the Master Curve method, K_{Jc} measured after irradiation can be directly used to construct a Weibull distribution, which is effective for the safety assessment of nuclear power plants [4–6]. This is now widely used in the service lifetime extension of nuclear power plants. Master Curve method will also be used in this paper to modeling K_{Jc} at different temperatures.

For the structural integrity of RPV, K_{Jc} should be tested for RPV irradiation surveillance program. Due to the large size of the standard compact tension specimen (1 CT) and the limited irradiation space in a RPV, small-size specimens are generally used for the sake of efficiency. However, how

to transfer K_{Jc} tested from small specimen to the standard specimen is questioning since there is crack tip constraint effect. For small-scale specimens, constraint loss may occur and extensive plastic deformation precedes unstable cleavage fracture. In such conditions, the evolving crack-tip plastic zones developing from the free surfaces affect strongly the levels of near-tip stress triaxiality (constraint) with increased loading [5]. Therefore, this paper employs the combination of experiment test and finite element analysis to study the influence of size (and crack tip constraint) effect on K_{Jc} and explores the link between different-sized specimens.

To date, there are a lot of methods to quantify constraint effect, e.g. small scale yielding correction (SSYC) [6,7], Q parameter [8,9] and the T stress [10–13]. Both Q parameter (Q stress, denoted as Q in the paper) and T stress give a quantitative value for the constraint effect. Neimitz and Dzioba [14] proposed an analytical formula to predict K_{Ic} of high strength steels in the transition region, considering both in-plane and out-of-plane constraint effects. They combined J_{Ic} and Q for the constraint analysis. Gao et al. [15] used T stress to predict T_0 variation between Single Edge Notch Bend specimens (SENB) with deep cracks and Compact Tension specimens (CT specimens) with deep and shallow cracks. Wallin [16] connected T_0 to the specimen constraint, expressed in terms of the T stress. It is shown that there is nearly a linear relation between T_0 and T stress

$$T_0 \approx T_{0deep} + \frac{T_{stress}}{10MPa/^{\circ}C} \text{ for } T \text{ stress [MPa]} < 0 \quad (1)$$

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<https://doi.org/10.1016/j.tafmec.2019.102370>

Received 17 June 2019; Received in revised form 16 September 2019; Accepted 20 September 2019

Available online 20 September 2019

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Nomenclature

a_0	initial crack length
A	total area under the load-displacement curve
A_p	area of the plastic section under the load-displacement curve
B_{xT}	actual specimen thickness $xT = 25.4 \times \text{mm}$
B	no side groove specimen thickness
B_0	1T thickness, 25.4 mm
B_N	net thickness of the open side groove specimen, for the side grooved specimen $B_N = B$
C	constant, taking different K_{JC} values for samples with different thicknesses
C_0	reciprocal of the slope of the elastic section of the load-displacement curve
D	variable
E	Young's modulus
J	J-integral
J_e	elastic part of J integral
J_p	plastic part of J integral
K	stress intensity factor
K_e	the elastic component of the stress intensity factor
K_{min}	threshold fracture toughness
K_0	scale parameter
K_{JC}	equivalent fracture toughness obtained by the transformation of the critical J integral

$K_{JC(\text{med})}$	median fracture toughness with a cumulative failure probability of 50%
M_{limit}	dimensionless deformation of the specimen specifying $M_{limit} = 30$
P_s	load at cleavage fracture
P_f	cumulative failure probability
Q	Q-stress
r	distance from the crack tip
T_0	fracture toughness ductile-brittle transition reference temperature
$T_{41J/28J}$	temperature corresponding to the impact absorption work of 28 J or 41 J
T-stress, T	Second term of William's extension along x direction
$T_{0\text{deep}}$	reference temperature obtained from deeply cracked (high constraint) specimens
W	specimen width
σ_y	yield stress at the test temperature
$\sigma_{\theta\theta}$	stress field existing before the geometric crack tip
$\sigma_{(\theta\theta)\text{ref}}$	reference solution which is obtained from the standard plane strain small-scale yield solution
ν	Poisson's ratio
δ_i	check constant
RPV	reactor pressure vessel
CT	compact tension
SSYC	small scale yielding correction
CMOD	crack mouth opening displacement

Minnebo et al. [17] investigated the fracture behavior of A533B steel in the transition region. They performed four series of K_{JC} tests to obtain T stress and T_0 values and found good agreement of T_0 by Eq. (1) and by experiments. However, for the elastic-plastic condition, the connection of Q parameter to K_{JC} is still lacking.

This paper aims to propose a link between the Q parameter and the reference temperature T_0 of difference sized specimens.

2. Experimental procedure and results

2.1. Experimental material

The material tested in this paper is the common RPV steel A508-3, the specific chemical composition is reported in Table 1.

In order to investigate the influence of size effect on K_{JC} , four sizes of specimens, 1CT, 0.5CT, 0.25CT and mini CT (1/6CT), were studied. The sizes of these specimens are: 60 mm $\times$ 62.5 mm $\times$ 25 mm, 30 mm $\times$ 31.2 mm $\times$ 12.5 mm, 15 mm $\times$ 15.6 mm $\times$ 6.3 mm, 10 mm $\times$ 10 mm $\times$ 4 mm. Crack depth a/W is 0.55 for all the tested specimens, as shown in Fig. 1. The 1/6CT specimens were taken from Charpy impact specimens. According to the standard ASTM E1921 [21], the test temperature range is required to be $T_0 \pm 50^\circ\text{C}$, and the test temperatures of the specimens of different sizes are shown in Table 2. K_{JC} test was carried out on a low temperature test on an ETM 304C microcomputer controlled electronic universal testing machine.

2.2. Master curve method

Wallin et al. [18–20] proposed a three-parameter Weibull formula to describe cumulative failure probability distribution of material toughness at a temperature in the ductile-brittle transition zone

$$P_f = 1 - \exp\left[-\frac{B}{B_0}\left(\frac{K_{JC} - K_{min}}{K_0 - K_{min}}\right)^4\right] \quad (2)$$

where P_f is the cumulative failure probability; K_{JC} is the equivalent fracture toughness obtained by the transformation of the critical J integral; B_0 is the reference specimen thickness, which is specified as 1 in.

of the specimen thickness, i.e. 1T; B is the actual thickness of the specimen, that is xT ; the scale parameter K_0 of the Weibull distribution is the K_{JC} value at $P_f = 63.2\%$; K_{min} is the threshold toughness of the threshold, taking a fixed value of 20, independent of the thickness and temperature of the specimen. The median K_{JC} curve with a failure probability of 50% is called Master Curve, and the expression is

$$K_{JC(\text{med})} = 30 + 70\exp[0.019(T - T_0)] \quad (3)$$

$K_{JC(\text{med})}$ means a specimen with thickness of 1T. Median K_{JC} of different thickness is converted to that of 1T by

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

The transition temperature T_0 of the Master Curve is determined by setting $K_{(\text{med})} = 100 \text{ MPa}\sqrt{\text{m}}$ in the Master Curve expression. Alternatively, the relationship between K_{JC} and the temperature T at any failure probability P_f is

Table 1
Nominal chemical composition of A508-3steel.

Element	Experiment material	National standard
C	0.18	0.16–0.22
Si	0.16	0.10–0.30
Mn	1.41	1.20–1.60
P	< 0.005	< 0.008
S	0.0027	< 0.008
Cr	0.12	≤ 0.2
Ni	0.75	0.50–0.80
Mo	0.46	0.43–0.57
Cu	< 0.02	≤ 0.08
V	0.005	≤ 0.01
Al	0.02	≤ 0.04
Co	< 0.02	≤ 0.03
As	0.003	≤ 0.010
Sn	0.002	≤ 0.010
Sb	0.0015	≤ 0.005
B	0.0002	≤ 0.0005

Fig. 1. Specimen geometry.

Table 2

Test temperature of specimens with different sizes.

1CT	-45 °C, -70 °C, etc.
0.5CT	-25 °C, -45 °C, -50 °C, -60 °C, -70 °C, -80 °C, -100 °C
0.25CT	-60 °C, -70 °C, -80 °C
1/6 CT	-80 °C, -90 °C, -100 °C

Fig. 2. Recorded load - crack mouth opening displacement curve.

Fig. 3. Valid data window of Master Curve.

$$K_{Jc}(P_f) = 20 + [-\ln(1 - P_f)]^{1/4} [11 + 77\exp(0.019(T - T_0))] \quad (5)$$

2.2.1. Test temperature selection

According to ASTM E1921-97 [21], methods of both single

Fig. 4. Master Curve modeling of K_{Jc} of all specimens. Fig. 5. Ductile-brittle transition reference temperature T_0 of specimens with different sizes.

temperature method and multi-temperature method for determining the reference temperature T_0 is provided for. The single temperature method requires at least 6–8 K_{Jc} data at a single temperature. The empirical formula for estimating the recommended test temperature T by the Charpy impact test is given as

$$T = T_{41J/28J} + C \quad (6)$$

where $T_{41J/28J}$ indicates the temperature corresponding to the impact absorption work of 28 J or 41 J. Several specimens were selected for groping until it was found that several fracture toughness values around

Fig. 6. Fracture surfaces of specimens with different sizes.

100 MPa $\sqrt{m}$ at a certain temperature.

It is considered that the critical J integral J_c at the time of cleavage fracture initiation can be decomposed into the elastic portion J_e and the plastic portion J_p .

$$J_c = J_e + J_p \quad (7)$$

For compact tensile CT specimens, the formula is as follows [21]:

$$J_e = \frac{(1 - \nu^2)K_e^2}{E} \quad (8)$$

$$K_e = \frac{P_s f(a_0/W)}{(BB_N W)^{1/2}} \quad (9)$$

$$f(a_0/W) = \frac{(2 + a_0/W)}{(1 - a_0/W)^{3/2}} \times [0.886 + 4.64(a_0/W) - 13.32(a_0/W)^2 + 14.72(a_0/W)^3 - 5.6(a_0/W)^4] \quad (10)$$

$$J_p = \frac{\eta A_p}{B_N b_0} \quad (11)$$

Taking the load-crack opening displacement curve of Fig. 2 as an example, point P_s is used as the parallel line of the straight line of the linear elastic section on the load-crack opening displacement curve, and the area under the curve is divided into two parts. The area A_p represents the work of plastic deformation of the specimen. The area A_e represents the work done by the elastic deformation of the specimen. The total area A under the curve is obtained by the integral load-crack mouth opening displacement curve.

$$A_p = A - \frac{1}{2} C_0 P_s^2 \quad (12)$$

For compact tensile CT specimens, the test generally records the load-displacement of the specimen. The η factor is as follows [21]

$$\eta = 2 + 0.522b_0/W \quad (13)$$

J_c is obtained from Eq. (7) and is converted to K_{Jc}

$$K_{Jc} = \sqrt{\frac{J_c E}{1 - \nu^2}} \quad (14)$$

2.2.2. Validity determination

The Master Curve method requires the specimen to be cracked to maintain a highly constraint state, so as to ensure T_0 independent of the

Fig. 7. Fracture surface of the 1/6CT specimen tested at different temperatures.

Fig. 8. Scanning electron micrograph of fracture surfaces of specimens with different sizes tested at -70°C .

Fig. 9. Relationship between the width of the dimple region and the specimen size.

specimen size. ASTM E1921 [21] requires that K_{JC} data not larger than $K_{JC(\text{limit})}$

$$K_{JC(\text{Limit})} = \sqrt{\frac{b_0 \sigma_{ys} E}{M_{\text{limit}} (1 - \nu^2)}} \quad (15)$$

The actual thickness of the specimen is not the standard 1T thick $B = xT$. The measured K_{JC} data should be converted into a 1T thick K_{JC} before the calculation of T_0 according to Eq. (4). The single temperature method is developed to perform fracture toughness test at the same temperature

Fig. 10. True stress-strain curve of specimen tested at -70°C .

$$K_0 = \sum_{i=1}^N \left(\frac{K_{JC(i)} - K_{\min}}{r} \right)^{1/4} + K_{\min} \quad (16)$$

N is the total number of specimens including the effective specimen and the invalid specimen, r is the number of effective specimens. The valid $K_{JC(i)}$ data is directly substituted into the calculation formula of K_0 . Invalid data greater than $K_{JC(\text{limit})}$ is replaced by $K_{JC(\text{limit})}$ and then substituted into the above formula, as shown in Fig. 3. If the K_{JC} data is invalid due to the stable crack propagation length exceeding the standard, the invalid K_{JC} data is the largest among all N specimens. The valid K_{JC} is substituted and then substituted into the above formula. Calculate the median fracture toughness $K_{JC(\text{med})}$ corresponding to 50%

Fig. 11. von Mises distributions of specimens with different sizes, note that the proportional size is not reflected in this figure.

Fig. 12. Modified boundary layer model used in J-Q method.

Fig. 13. Relationship between Q and specimen size.

cumulative failure probability after K_0 is determined,

$$K_{JC(med)} = (K_0 - 20)(\ln 2)^{1/4} + 20 \quad (17)$$

Finally, the following formula is used to calculate T_0

$$T_0 = T - \frac{1}{0.019} \ln \left[\frac{K_{JC(med)} - 30}{70} \right] \quad (18)$$

If T_0 is calculated by the multi-temperature method, the calculation formula is as follows

$$\begin{aligned} & \sum_{i=1}^N \delta_i \exp(0.019(T_i - T_0)) / \{11 + 77 \exp[0.019(T_i - T_0)]\} \\ &= \sum_{i=1}^N (K_{JC(i)} - 20)^4 \exp[0.019(T_i - T_0)] / \{11 + 77 \exp[0.019(T_i - T_0)]\}^5 \end{aligned} \quad (19)$$

In the above formula, $K_{JC(i)}$ is the converted K_{JC} of 1 T. δ_i is the check constant. $\delta_i = 1$ when the data is valid, and $\delta_i = 0$ when the data is invalid.

Fig. 14. The relationship between T_0 value and Q value for specimens of different sizes.

3. Results

3.1. Fracture toughness data

According to ASTM E1921, the multi-temperature method requires all data in the calculation of T_0 . In this way, results are fitted according to Master Curve and are summarized in Fig. 4. All K_{JC} of different sizes were converted into that of the standard 1CT specimen according to Eq. (4) and are compared in Fig. 4. The Master Curve and the upper and lower boundaries of 95% and 5% well predicted the distribution of fracture toughness (thickness converted to 1T) of the A508-3 steel CT specimen in the ductile-brittle transition zone. As the size decreases, constraint decreases and the number of invalid data increases.

K_{JC} increases with the test temperature. It is seen that the data is valid when 1CT specimen is tested at -45°C , and the invalid data has appeared at -45°C for the 0.5 CT specimen. Invalid data appeared at -60°C for 0.25 CT specimens. The test temperature was lowered and constraint was increased and the data was valid. Invalid data appeared when the smallest 1/6CT specimen was tested at -70°C . It is shown that as the specimen size decreases, specimen constraint decreases. At the same temperature, the smaller the size, the greater the possibility of invalid data.

T_0 of different specimens is shown in Fig. 5. It is seen that T_0 of 1/6 CT, 0.25CT, 0.5CT and 1CT specimen are -72.68°C , -68.36°C , -64.73°C and -63.22°C , respectively. It is shown that T_0 decreases as the size decreases, and the maximum and minimum value differs by 9.46°C . This indicates that small specimens are not able to replace the larger specimen in the surveillance test, which affects the prediction of fracture toughness by more than 13%. Therefore, further correction of the data is required to ensure that small specimens have the same reliability as standard specimens in the prediction of K_{JC} .

3.2. Fracture surface analysis

Typical fracture surfaces of the specimens with different sizes are shown in Fig. 6. The transverse line shape in the middle is a pre-fabricated fatigue crack. The fatigue crack part is the crack instability extension part in the pre-fabricated fatigue. It is further shown in Fig. 7 the fracture surface of the mini (1/6) CT specimens tested at -100°C , -90°C , and -80°C observed with scanning electron microscope. In the lower temperature the fracture surface demonstrates a more brittle fracture mode. For the specimen tested at -80°C , there is a large amount of dimple fracture area near the pre-fabricated fatigue crack. As the temperature decreases, the dimple part decreases and gradually turns into a cleavage part, which is an obvious fan-shaped cleavage plane.

Scanning electron micrographs for the fracture surfaces of the specimens with different dimensions tested at -70°C are shown in Fig. 8. It is seen that the dimple zone in the 1CT specimen is the narrowest, which shows more cleavage fracture pattern. For the 1/6CT specimen, the dimple zone in the fracture surface increases significantly. The dimple zone size for all the specimens is further quantified in Fig. 9. As the specimen size decreases from 1CT to 1/6 CT, the dimple band gradually widens. This is consistent with the variation of T_0 with the specimen size. This further confirms that the constraint of the small-size specimen is reduced and the plane strain condition is hard to be satisfied. Therefore, it is necessary to increase the stress concentration at the crack tip, so that the cleavage fracture can occur under the applied load. It is important to quantify the constraint between plane stress and plane strain condition.

4. Finite element simulation

Two-dimensional models corresponding to 1CT, 0.5CT, 0.25CT, and 1/6CT specimens are built with the ABAQUS software based on elastic-plastic fracture mechanics. The stress-strain curve at temperature of -70°C is shown in Fig. 10. The elastic modulus is 195 GPa and yield strength is 488 MPa. The true stress-strain curve is determined from engineering stress-strain curve, which is obtained from the experiment test. In the calculation, the plastic behavior of the material is assumed to follow the Ramberg-Osgood model. Displacement is applied in the rigid body according to the experiment.

The influence of constraint on the stress field at the crack tip of the specimen was studied, and the stress field distribution of the specimens of different sizes was observed. The quadratic 20-node hexahedron element (C3D20 element) is used for the finite element simulation. In order to simulate the stress singularity, the brick element is converted to a wedge element (C3D15 element). By moving the mid-point nodes to the one-quarter point and keeping the nodes on the cracked face the singularity effect will follow the law of inverse square root, i.e., for the crack front, hence avoiding the use of additional singularity elements in finite element simulation. A middle point in the symmetrical line is fixed. Element meshes, von Mises distribution of the specimens are shown in Fig. 11.

4.1. Constraint analysis by J-Q theory

In order to properly transfer K_{Jc} tested between different specimens, J-Q theory is used to quantify the crack tip constraint. Under small-scale yield conditions, constraint is usually evaluated by comparing the stress field calculated by the finite element method with the stress field obtained from the reference solution of the high triaxiality.

The J-Q theory is used by many researchers to describe the near-tip stress field of two-dimensional and three-dimensional geometries. Wang [22] demonstrated that the Q parameter as a measure of the difference between the actual open stress and the small-scale yield solution is accurate for the range of the normalized radial distance. In the analysis presented by Silva et al. [23], plane-strain results produce

relatively unchanged Q values when the normalized radial distance from the crack tip is varied between $1 < r/(J/\sigma_y) < 5$. Thus, the crack tip constraint is properly quantified by Q. Q is defined as

$$Q = \frac{[\sigma_{\theta\theta} - \sigma_{(\theta\theta)ref}]}{\sigma_y}, \quad \theta \leq 90^\circ, \quad r = 2J/\sigma_y \quad (20)$$

In this study, Q is calculated to quantify the crack tip constraint of the four different specimens. Fig. 12 shows the modified boundary layer model mesh and displacement boundary conditions. As shown in Fig. 13, Q decreases as the size decreases, indicating that the specimen constraint decreases as the size decreases. In this condition, plane strain may gradually changes to plane stress. This may affect K_{Jc} prediction inaccurate. Therefore, a method to transfer K_{Jc} among different specimens is needed.

5. K_{Jc} transfer model

Combining the finite element results with the experimental data, a model for predicting the ductile-brittle transition reference temperature T_0 of A508-3 was established. The relationship of T_0 between specimens with different geometry is developed considering Q. Suppose

$$T_{0(1T)} = T_{0(xT)} + D \exp(B_Q) \quad (21)$$

B_Q is a function of the Q value, and $T_{0(1T)}$ is the ductile-brittle transition reference temperature T_0 of the standard 1CT specimen. Substituting T_0 of the different specimens obtained in the experiment and Q calculated in the finite element analysis, the following formula is obtained

$$T_{0(1T)} = T_{0(xT)} + 16 \exp\left[\left(-\frac{Q}{7.4}\right) \exp(-4)\right] \quad (22)$$

For the A508-3 steel used in the paper, $T_{0(1T)} = -63.22^\circ\text{C}$. Comparing the above formula with the data, it is seen that the curve fits well with the data, as shown in Fig. 14. With Eq. (22), T_0 of different specimens is corrected. The model is used to convert T_0 between different specimens (xT) and standard 1CT specimens. In this way, the irradiation surveillance specimen in a RPV is used properly in K_{Jc} modeling.

6. Conclusions

In this paper, a series of fracture toughness test were performed for specimens with different sizes. Crack tip constraint effect was studied using J-Q theory. The following conclusions are drawn based on the present study:

1. As the specimen size increases, it is confirmed that the ductile-brittle transition temperature T_0 increases. Due to the big differences in T_0 tested by different specimens, the small specimen is not able to replace the standard specimen to predict K_{Jc} of the RPV steel in the surveillance program.
2. At the test temperature -70°C , scanning electron micrograph of the fracture surface shows that dimple zone in the 1CT specimen is the narrowest, which demonstrates the most obvious cleavage fracture pattern. The width of the dimple region increases significantly with the specimen size.
3. Considering constraint effect of different specimens using Q, a model is proposed to convert T_0 between different specimens.

It is further planned to model K_{Jc} with other local approach to fracture (multiscale, multiaxial) and a new probabilistic framework is planned for the uncertainty analysis [24–28]. Some new design of the structures inspired from composite materials made with the additive manufacturing technique may be helpful for future RPV material [29–31].

Declaration of Competing Interest

We hereby declare that there is no conflict of interest. This paper (or closely related research) has not been published or accepted for publication. It is not under consideration at another journal.

Acknowledgements

Financial support by Large-scale Advanced PWR Nuclear Power Plant Major Projects (2018ZX06002008), by National Natural Science Foundation of China (No. 11872364) and by CAS Pioneer Hundred Talents Program is acknowledged.

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