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Correction of constraint loss in fracture toughness measurement of PCVN specimens based on fracture toughness diagram[†]

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Abstract

The aim of this paper is to suggest an approach to generate master curves by using miniature specimens, especially pre-cracked Charpy V-notched (PCVN) specimen, made of SA508 carbon steel. Firstly, fracture toughness diagram is derived from comparing finite element analyses results with the fixed mesh size at crack tip between standard compact tension and PCVN specimens. To compensate the constraint effects from different geometry, further examination based on the fracture toughness diagram was performed. In this context, a scale factor to deal with specimen size effects is proposed by statistically manipulating the numerical analysis data. Finally, the proposed scale factor is applied to calculate reference temperature which affects on the master curve. We expect that the approach can be applicable to compensate the geometrical constraint effects on fracture toughness of SA508 carbon steel when the PCVN specimen is used.

Keywords: Fracture toughness diagram; Pre-cracked Charpy V-notched specimen; Reference temperature; Size effect

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1. Introduction

ASTM E1921 [1] provides a standard test method to obtain fracture toughness data representing cleavage resistance of ferritic steels. Test results show large scatters in the ductile to brittle transition temperature (DBTT) region. In order to properly describe the scatter of fracture toughness values in transition temperature and lower shelf regions, Wallin [2, 3] proposed the master curve method. With regard to this method, the equation of size effect predictions embodied in ASTM E1921 is used to calculate the equivalent fracture toughness to a reference sized specimen, which is an important parameter to determine the reference temperature represented as T_0. Fracture toughness is significantly dependent on specimen sizes while most of tests are carried out using relatively small while specimens such as surveillance coupons. So, in the master curve method, the size effect of miniature specimen has to be exactly incorporated.

A fracture toughness diagram which deals with a relationship between Weibull stresses and J-integrals is one of useful tools to predict the size effect. The Weibull stress micromechanical model [4, 5] or local approach is based on the weakest link theory and uses statistics. It has been effectively applied for elastic-plastic structural integrity and damage mechanics assessment. In this paper, the fracture toughness diagram is derived from finite element (FE) analyses data of compact tension (CT) specimens and pre-cracked Charpy V-notched (PCVN) specimens. Further, an approach to generate master curves by using small size PCVN specimens made of SA508 carbon steel is suggested. In this context, the remainder of paper is organized as follows: In section 2, ASTM E1921 and conventional master curve method are reviewed. Then, detailed FE analysis method and results are described in section 3. Also, the fracture toughness diagram is derived based on FE analyses results. In section 4, a scale factor to deal with the size effect is proposed to calculate the reference temperature and therby the master curve.

2. Conventional master curve

2.1 Brief review of ASTM standard

ASTM E1921 presents a direct method, which is called as the master curve method, to obtain fracture toughness values of ferritic steels that experience onset of cleavage cracking at transition temperature region. Since the fracture toughness is influenced by specimen thickness in the transition range, the equation of size effect predictions embodied in ASTM E1921 is as follows:

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$$K_{Jc}^{1T} = K_{\min} + [K_{Jc}^{xT} - K_{\min}]\left(\frac{B_{xT}}{B_{1T}}\right)^{1/4} \tag{1}$$

where K_{Jc}^{xT} is the K_{Jc} for a specimen size B_{xT}, B_{xT} is the gross thickness of test specimens (side-grooves ignored), B_{1T} is the gross thickness of prediction (side grooves ignored) and $K_{\min}$ is 20MPa√m (18.2ksi√in).

2.2 Mechanical properties and fracture toughness data

Tensile tests on typical SA508 carbon steel were carried out at -60°C and -80°C as illustrated in Fig. 1 [6]. Representative mechanical properties such as the values of elastic modulus (E), Poisson's ratio (ν) and yield strength (σ_{YS}) of the material are 196GPa, 0.3 and 502MPa at -60°C. To describe plastic behavior of material, Ramberg-Osgood (R-O) relationship was used. R-O parameters such as the value of α and n of SA508 carbon steel are 2.43 and 7.03 at -60°C, and those are 2.41 and 6.77 at -80°C, respectively.

Fracture toughness tests were performed by the ASTM E1921 standard [6]. To obtain fracture toughness values, 10x10mm PCVN specimens without side-grooves were used. Table 1 summarizes the fracture toughness data at -60°C and -80°C.

2.3 Master curves by single-temperature procedure

Fig. 2 shows the procedure of master curve method, which enables to describe deviating fracture toughness behaviors.

The master curve method can be applied by two procedures such as single temperature estimation and multi temperature estimation [7]. In the former, T_0 is calculated from the size adjusted $K_{Jc\,(\mathrm{med})}$ values using Eq. (2).

Table 1. Fracture toughness test data of SA508 carbon steel.

Temperature (°C)	J_c (kJ/m^2)
-60	80.8, 90.8, 91.6, 91.8, 113.2, 136.3, 144.0, 166.7
-80	91.9, 33.6, 45.3, 60.4 70.0, 80.4, 100.0

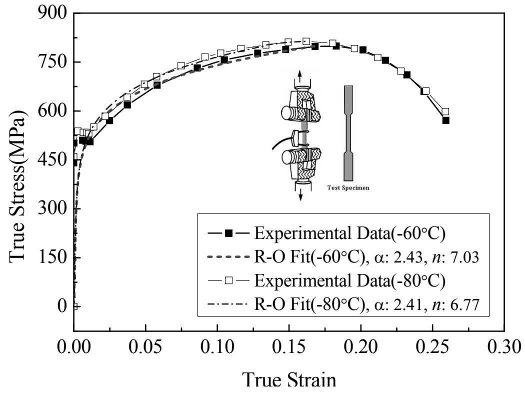


Fig. 1. Tensile test data of SA508 carbon steel.

$$T_0 = T - \left(\frac{1}{0.019}\right)\ln\left[\frac{K_{Jc(med)} - 30}{70}\right] \tag{2}$$

where T_0 is the reference temperature, T is the test temperature and $K_{Jc\,(med)}$ is the median K_{Jc} toughness.

2.4 Master curve by multi-temperature procedure

The multi-temperature procedure of ASTM E1921 represents an option for the determination of T_0 with K_{Jc} values distributed within a restricted temperature range, namely T_0±50°C. The value of T_0 can be evaluated by an iterative scheme of Eq. (3):

$$\sum_{i=1}^{n}\delta_i\frac{\exp[0.019(T_i - T_0)]}{11 + 77\exp[0.019(T_i - T_0)]} - \sum_{i=1}^{n}\delta_i\frac{(K_{Jc(i)} - 20)^4\exp[0.019(T_i - T_0)]}{\{11 + 77\exp[0.019(T_i - T_0)]\}^5} = 0 \tag{3}$$

where n is the number of specimens tested, T_i is the test temperature corresponding to $K_{Jc\,(i)}$, $K_{Jc\,(i)}$ is either a valid K_{Jc} datum or dummy value substitute for and invalid datum. δ_i is 1.0 if the datum is valid or zero if the datum is a dummy substitute value.

3. Fracture toughness diagram

3.1 Concept of fracture toughness diagram

Dodds Jr. et al. [8-11] suggested a simple toughness scale method (TSM). Since this method couples the ASTM E1921 procedure with the Weibull stress model, it is possible to correlate K_{Jc}^{xT} and K_{Jc}^{1T} via Weibull stress. In this paper, FE analyses were carried out for standard CT specimens and their results were compared with those of PCVN specimens. Then, the fracture toughness diagram was generated based on the simple TSM.

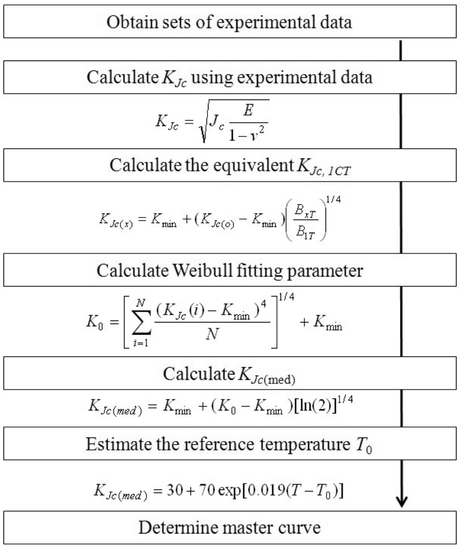


Fig. 2. The procedure of master curve method.

3.2 Finite element analyses

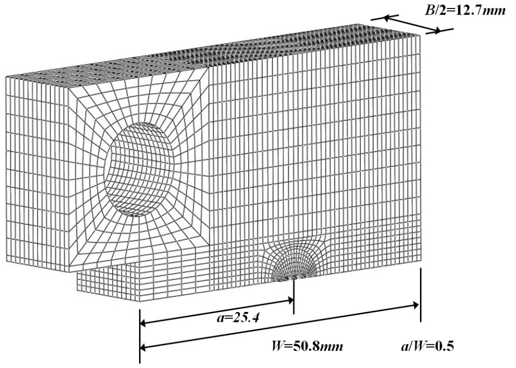
A series of detailed FE analyses were performed by using the R-O parameters. Materials were modeled to depict isotropic elastic-plastic behaviors that obey J_2 flow theory, and a small geometry change continuum FE model was employed. *J*-integral values were extracted from general-purpose FE program, ABAQUS [12].

The Weibull stress model requires attainment of equivalent stressed volume ahead of a crack front for cleavage fracture. In order to examine effects of mesh sizes at crack-tip, two types of FE models such as the proportional mesh [13] and the fixed mesh were compared. As a result, maximum difference between the proportional and fixed mesh size at crack tip was 17%. In this paper, FE models of the same mesh size at crack-tip were adopted because it could be better describe the constraint effect.

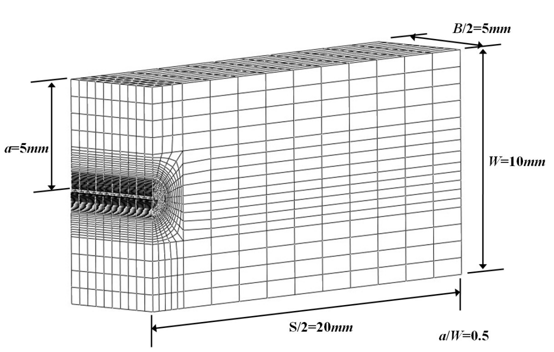
Fig. 3 illustrates CT and PCVN meshes used in FE analyses. The quarter model of 1T-CT, 1/2T-CT and 1/3T-CT consists of 19,525 nodes and 16,640 elements. Also, the quarter model of 3.3x3.3mm, 5x5mm and 10x10mm PCVN specimens consists of 11,594 nodes and 9,740 elements. The crack aspect ratio (*a*/*W*) is set to 0.5.

3.3 Derivation of facture toughness diagram

To derive the fracture toughness diagram, relationship between the Weibull stresses and *J*-integrals of CT and PCVN specimens was calculated. *J*-integral of PCVN specimen has larger value than that of CT specimen at the given Weibull stress. This can be explained by that the CT specimen is easier to initiate cleavage fracture than the relatively thin PCVN specimen. Fig. 4 shows the fracture toughness diagram under various sizes and temperatures, which can be used to define failure characteristics of SA508 carbon steel during the cleavage fracture and predict size effects for calculating the reference temperature in use of PCVN specimens.



(a) 1T-CT specimen



(b) 10x10mm PCVN specimen

Fig. 3. Geometry and FE model of CT and PCVN specimen.

3.4 Size effect predictions

Eq. (1) is widely used to adjust the size effect of diverse specimens for fracture toughness test. However, ASTM E1921 over-predicts than the fracture toughness diagram in case of PCVN specimens [14]. To reduce this unconservatism, the scale factor was suggested and its effects are shown in Fig. 5. Therefore, it is desirable to modify Eq. (1) like Eq. (4). The scale factor for PCVN specimens with various sizes is summarized in Table 2.

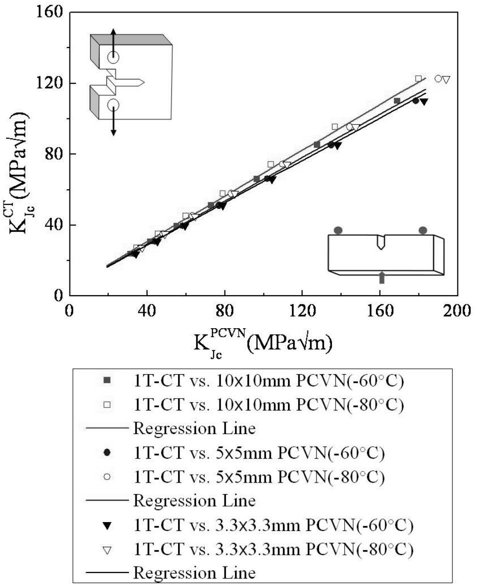


Fig. 4. Fracture toughness diagram under various sizes and temperatures.

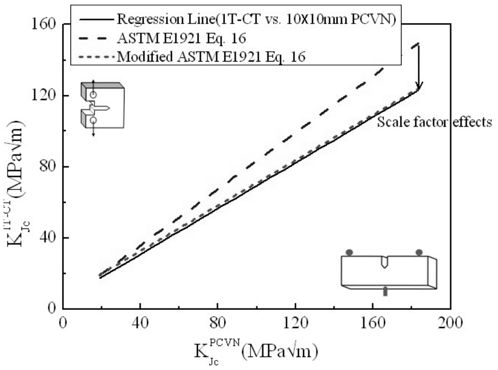


Fig. 5. Scale factor effect.

Table 2. Estimated scale factor for various sizes of PCVN specimen.

PCVN specimen	Scale factor
10x10mm	0.42
5x5mm	0.65
3.3x3.3mm	0.9

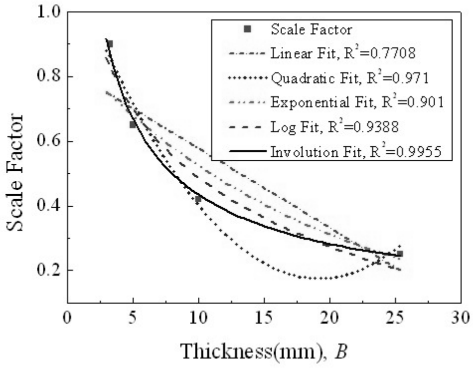


Fig. 6. Numerical investigation of scale factors.

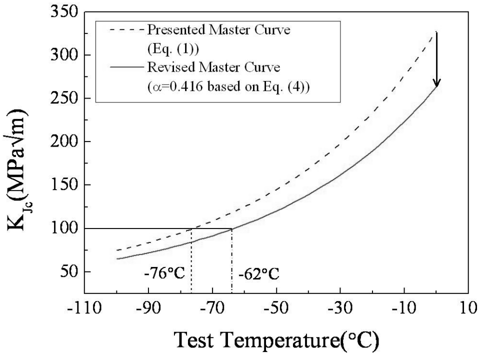


Fig. 7. Comparison of $K_{Jc\,(\mathrm{med})}$ in use of Eq. (1) and Eq. (4).

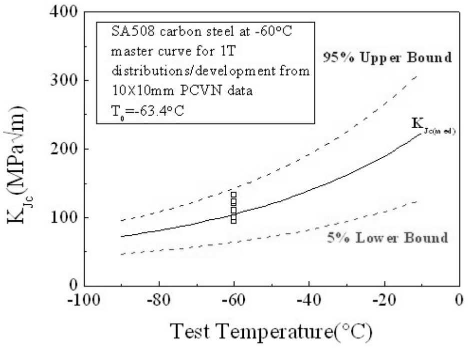
To find out the relationship between specimen's thickness and scale factors, statistical investigation such as linear fit, quadratic fit, exponential fit, log fit and involution fit were performed. During this process, 25.4x25.4mm PCVN specimen comparable to the standard 1T-CT specimen was additionally modeled and analyzed. As indicated in Fig. 6, the involution fit provides optimum results to explain the size effect. So, with regard to PCVN specimen, the following equation is proposed for size effect estimation.

$$K_{Jc}^{1T} = K_{\min} + [K_{Jc}^{xT} - K_{\min}]\left(\frac{\alpha B_{xT}}{B_{1T}}\right)^{1/4} \qquad (4)$$

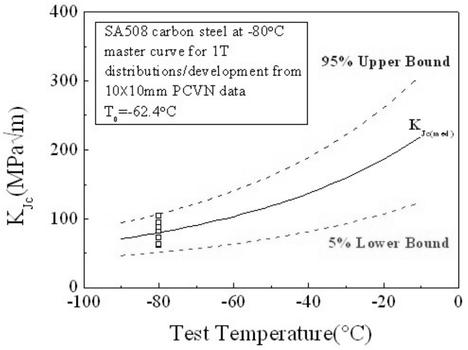
$$\alpha = 1.998 \times B_{xT}^{-0.682}$$

where α is the scale factor.

Meanwhile, the aforementioned finding affects the master curve method because K_{Jc} in Eq. (4) is used to calculate the reference temperature. At the given $K_{Jc\,(\mathrm{med})}$, 100MPa√m, the reference temperature of conventional master curve is lower than that of the revised master curve as indicated in Fig. 7. This agrees with a well-known constraint effect between 1T-CT and PCVN specimens [1].



(a) -60°C



(b) -80°C

Fig. 8. Modified master curve determined by using Eq. (4) and single temperature procedure.

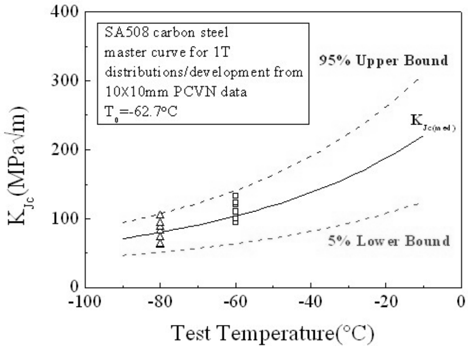


Fig. 9. Modified master curve determined by using Eq. (4) and multi temperature procedure.

4. Modified master curve

4.1 Modified master curves by single-temperature procedure

In this section, the scale factor obtained from fracture toughness diagram was utilized for quantification of the size effect. The scale factor influences on the reference temperature in master curve because the equivalent K_{Jc}^{1T} is needed to calculate it as described in Fig. 2. Fig. 8 shows the master curve determined by using Eq. (4) and the single-temperature procedure.

Table 3. Reference temperature under various conditions.

Case	Description	T_0 (°C)
1	10×10mm PCVN data, Eq. (1), single temperature (-60°C)	-76.2
2	10×10mm PCVN data, Eq. (1), single temperature (-80°C)	-75.7
3	10×10mm PCVN data, Eq. (1), multi temperature (-60°C & -80°C)	-75.9
4	10×10mm PCVN data, Eq. (4), single temperature (-60°C)	-63.4
5	10×10mm PCVN data, Eq. (4), single temperature (-80°C)	-62.4
6	10×10mm PCVN data, Eq. (4), multi temperature (-60°C & -80°C)	-62.7

4.2 Modified master curve by multi-temperature procedure

Fig. 9 depicts a master curve determined by using Eq. (4) and the multi-temperature procedure.

4.3 Comparison of reference temperature

Reference temperatures obtained from aforementioned various conditions are compared in Table 3.

4.4 Discussion

As shown in Fig. 5, Eq. (1) over estimates material resistance than fracture toughness diagram when using PCVN specimens. As a result, at the given $K_{Jc\ (\mathrm{med})}$ value of 100MPa√m, the reference temperature of conventional master curve is -76°C and that of revised master curve is -62°C. It implies that necessity of appropriate scale parameters to resolve crack-tip constraint effect cause by different geometries. So, in this paper, a promising scale factor is suggested. The effectiveness was proven by its application to determine master curves. When fracture toughness estimation is performed using PCVN specimens, the proposed approach may be used to correct a constraint effect on fracture behavior.

5. Conclusion

This work was to suggest a useful approach to determine the master curve in use of miniature specimens. To do this, fracture toughness diagram was derived from detailed FE analyses data of standard CT and small size PCVN specimens. Then, the optimum scale factor to correct a geometrical constraint effect was proposed as a form of Eq. (4) and used for determination of the master curves as well as reference temperatures. We expect that the approach can be applicable to estimate realistic fracture behavior of SA508 carbon steel when the PCVN specimen constraint effects are taken into account.

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