Small Scale Yielding Correction of Constraint Loss in Small Sized Fracture Toughness Test Specimens

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1. Introduction

Fracture toughness data in the ductile-brittle transition region of ferritic steels show scatter produced by local sampling effects and specimen geometry dependence which results from relaxation in crack tip constraint. The ASTM E1921 [1] provides a standard test method to define the median toughness temperature curve, so called Master Curve, for the material corresponding to a 1T crack front length and also defines a reference temperature, T_0, at which median toughness value is 100 MPa√m for a 1T size specimen. The ASTM E1921 procedures assume that high constraint, small scaling yielding (SSY) conditions prevail at fracture along the crack front. Violation of the SSY assumption occurs most often during tests of smaller specimens. Constraint loss in such cases leads to higher toughness values and thus lower T_0 values. When applied to a structure with low constraint geometry, the standard fracture toughness estimates may lead to strongly over-conservative estimates. A lot of efforts have been made to adjust the constraint effect. In this work, we applied a small-scale yielding correction (SSYC) to adjust the constraint loss of 1/3PCVN and PCVN specimens which are relatively smaller than 1T size specimen at the fracture toughness Master Curve test.

2. Crack Tip Constraint Adjustment Procedure

The SSYC method [2, 3] tries to directly quantify the effect of constraint on toughness by scaling the stress distribution in front of the crack to corresponding to the high constraint situation. Odette and He[4] applied the SSYC method to adjust for the constraint effect by combining analytical representations of finite element analysis simulations of crack tip stress fields with a local critical stress - critical stressed area (σ^*-A^*) fracture criterion, assuming that σ^* and A^* are independent of temperature.

As shown in Fig. 1, first, in this method 2D plane strain SSY finite element analysis are performed to obtain the non-dimensional in-plane area, A/b^2, enclosed within a specific stress contour and the applied loading parameter $(J/b\sigma_0)^2$ which varies linearly with the A/b^2, where b and σ_0 are uncracked ligament and yield stress respectively, and J means fracture toughness. As the crack-tip stress fields gradually enter a regime of large-scale yielding (LSY) condition, the magnitude of σ_{22} stresses deviate from SSY values at moderate to high levels of specimen deformation, where the stress field ahead of crack tip experiences a reduction of triaxiality, resulting in a constraint size effect. In LSY condition, as seen in Fig. 1, A/b^2 no longer varies linearly with $(J/b\sigma_0)^2$. We solved 3D finite element model for PCVN specimens to obtain the crack tip stress field for LSY condition.

Following completion of the 2D plane strain SSY, 3D LSY finite element simulation and postprocessing of the results, adjustments from LSY to SSY based on common stressed area can be calculated at each deformation level, using J values, as shown in Fig. 1. The common stressed area A^* and the stress ratio σ^*/σ_0 are chosen to provide the best fit to the mean experimental data.

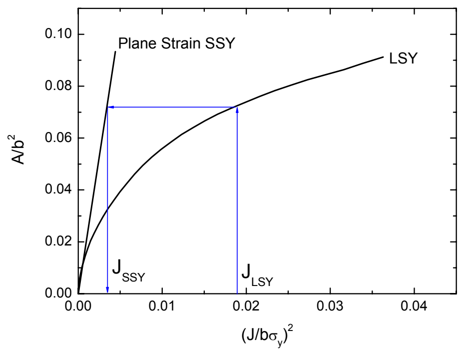

Figure 1 LSY to SSY adjustment procedure

In the finite element analysis, temperature dependent elastic moduli of test materials were calculated from E= 207200-57.09T (MPa,℃). The power-law hardening stress-strain relationship was assumed as $\sigma=K\varepsilon^n$, where K=1008-1.99T (MPa), n=0.156 (-160℃<T< 0℃).

Following adjustment to plane strain SSY, the results were then adjusted to a common 1T reference thickness thorough:

$$K_{Jc}^{E1921(1T)} = K_{\min} + (K_{Jc}^{xT} - K_{\min})\left(\frac{B_{xT}}{B_{1T}}\right)^{1/4} \qquad (1)$$

where K_{min} is taken to be 20 MPa√m as recommended in ASTM E1921.

3. Experiments

Test materials, in this work, were taken from an actual scale SA508-Gr. RPV forging thicker than 200mm. 1/3PCVN, PCVN and 1T-CT specimens were sampled from only the 1/4T location of each block. The orientation of the specimen is T-L direction. Fracture toughness was measured in accordance with ASTM E1921 standard procedure. The load-line displacement rate in the fracture toughness test was 0.5min/min. Six or more specimens were tested at single temperature, and the fracture toughness Master Curve and T_0 were calculated in accordance with ASTM E1921 standard procedure. Table 1 shows each test temperature, number of used specimens and calculated T_0 values.

Table 2 Specimens used in Master Curve test and FE analysis

Specimen Type	1T-CT	PCVN	1/3PCVN
Temperature(℃)	-60	-100	-140
Number of Specimen	6	9	10
T_0 (℃)	-75.7	-87.1	-89.5

4. Results and Discussion

Following ASTM E1921, the resulting K_{Jc} values are plotted with respect to temperature in Fig. 2. A solid line is median K_{Jc} curve of 1T size specimen with reference temperature, T_0=-75.7℃, and dotted lines represent 5% and 95% bound level of Master Curve. The opened symbols are measured K_{Jc} values. Fig. 3 shows toughness results when analyzed through the SSYC method, including the ASTM E1921 censoring procedure. Fig. 4 plots the T_0 values calculated with constraint effect addressed using the ASTM E1921 censoring procedure (square symbols) and the SSYC methods (triangle symbols) respectively. These differences may originated from the M=30 value assumed in ASTM E1921. It was demonstrated that constraint effects become significant beginning at M=100 [5].

5. Conclusion

The SSYC method was applied to the results of the size effect study of fracture toughness in transition region and facilitated by detailed 3D LSY and 2D plane strain boundary layer SSY FE models. Post processing procedure and program to apply the SSYC to the small size specimens, 1/3PCVN and PCVN, were established. The SSYC technique can be used to obtain a specimen size independent measure of transition toughness.

Acknowledgement

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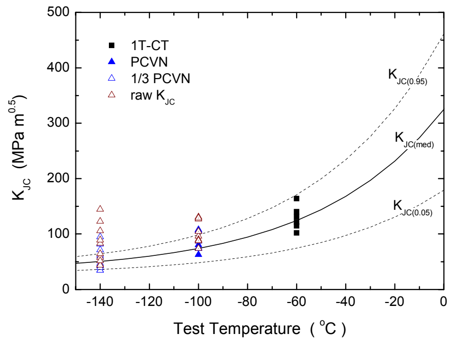

Figure 2 Master Curves calculated using ASTM E1921

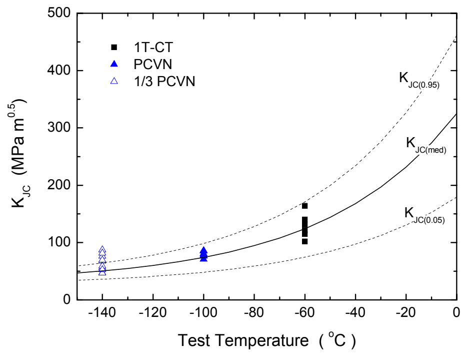

Figure 3 Master Curves after LSY to SSY adjustment

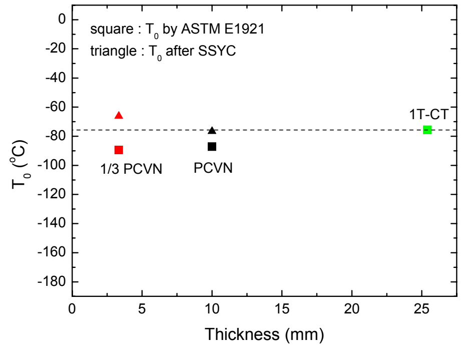

Figure 4 Comparison of T_0 Calculation

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