Strength Mismatch Effects on Charpy Absorbed Energy and CTOD Fracture Toughness*

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In order to examine the difference between the sensitivity of Charpy absorbed energy, $\sqrt{E}$, and critical CTOD, δ_{cr} , to strength mismatch in welds, the numerical analysis was conducted. This study adopted the evaluation method based on the Weibull stress criterion for calculation of $\sqrt{E}$ and δ_{cr} assuming that the critical Weibull stress at brittle fracture is independent of the strength mismatch as well as the loading rate.

This analysis showed that the $\sqrt{E}$ and δ_{cr} decreased as the location of the V-notch or crack approached welded interface. The change in $\sqrt{E}$ was larger than that in δ_{cr} , because the strength mismatch caused acceleration of strain rate and decrease in temperature rise near the V-notch as well as plastic constraint. This result indicates that the sensitivity of the $\sqrt{E}$ and δ_{cr} to strength mismatch is different depending on the loading rate.

Key Words: Notch toughness, Fracture toughness, Weibull stress, Brittle fracture, Strength mismatch, Impact loading

1. Introduction

Fracture toughness values are often estimated from the Charpy absorbed energy, $\sqrt{E}$ by using empirical correlation. The correlation taking account of a temperature shift due to difference in loading rate between Charpy impact test and fracture toughness test was obtained for steels¹⁾. If the correlation is applicable to welds, it is useful for estimating fracture toughness of welds.

It is concerned that the strength mismatch affects the correlations between the $\sqrt{E}$ and critical CTOD, δ_{cr} . It is reported that the strength mismatch affects $\sqrt{E}$ ^{2,3)} and the δ_{cr} ⁴⁾ respectively. When there is the hardened part around the V-notch or crack, the $\sqrt{E}$ and δ_{cr} decrease. This is caused by plastic constraint. The Charpy specimen is subjected to dynamic loading, whereas the fracture toughness specimen is subjected to static loading. The flow stress is elevated and the toughness is deteriorated by acceleration of strain rate¹⁾. The strain rate for Charpy specimen is affected by the strength mismatch³⁾. Thus, in addition to the plastic constraint, the effect of the loading rate should be taken in consideration.

In this paper, numerical analysis based on Weibull stress approach on brittle fracture was conducted in order to investigate the influence of strength mismatch on $\sqrt{E}$ and δ_{cr} . The stress fields were analyzed for Charpy specimen and CTOD specimen of welded joint of dissimilar steels.

2. FE analysis procedure

The stress fields in the Charpy specimen and the 3PB specimen were analyzed with ABAQUS Standard ver-6.12. The configurations of the V-notched Charpy specimen and the three-point-bend (3PB) specimen employed in the FE analysis are shown in Fig. 1. The target of this analysis was the welded joint of dissimilar steels, which had notch or crack in softer material. The CTOD fracture toughness specimen of base metal (CTOD-B-specimen) and the Charpy specimen of base metal (CVN-B-specimen) are shown in Fig. 1(a) and Fig. 1(c),

Fig. 1 Schematic illustration of the target in this study

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respectively. The CTOD fracture toughness specimen of welded joints (CTOD-J-specimen) is shown in Fig. 1(b), and V-notch Charpy specimen of welded joints (CVN-J-specimen) is shown in Fig. 1(d). The Charpy specimen has the standard 2 mm V-notch parallel to the welded interface (or fusion line, FL). The 3PB specimen has the sharp crack parallel to FL, whose length a is $W/2$, where the W means the width of specimen. The distance from FL to V-notch or crack, d was varied from 1 mm to 5 mm. The FE models used is shown in Fig. 2. Because of symmetry of the specimen, one quarter of the CVN-B- and the CTOD-B-specimen, and one half of the CVN-J- and the CTOD-J-specimen were modeled. The FE analysis used the eight-node element with eight Gaussian integration points, and the minimum element size near the notch root and crack tip had dimensions of $0.05 \times 0.05 \times 0.2$ mm.

In the FE analysis, the power-hardening law of Swift type was adopted:

$$\bar{\sigma} = \sigma_Y \left(1 + \bar{\varepsilon}_p / \alpha\right)^n \quad (1)$$

where $\bar{\sigma}$ and $\bar{\varepsilon}_p$ are the equivalent stress and equivalent plastic strain, respectively, σ_Y is the yield stress, and n and α are material constants (n being a strain-hardening coefficient). The Young's modulus, E , and Poisson's ratio, ν , are 206,000 MPa and 0.3, respectively. The mechanical properties of

Fig. 2 FE models used in this study

Table 1 Mechanical properties used in FE analysis

Material	σ_Y (MPa)	σ_T (MPa)	σ_Y/σ_T	ε_T (%)
TS400	300	400	0.75	26
TS800	720	800	0.90	10

σ_Y : Yield stress, σ_T : Tensile strength, ε_T : Uniform elongation

Table 2 Thermal constants used in FE analysis

C (J/kg·K)	ρ (kg/mm ³)	λ (W/K·m)	α_L (1/K)
4.69×10^2	7.86×10^{-6}	51.8	1.2×10^{-5}

C : Specific heat, ρ : Density, λ : Thermal conductivity,
 α_L : Coefficient of liner expansion

elastic-plastic materials at the room temperature and static loading rate used in this study are shown in Table 1.

In the FE analysis of the Charpy impact test, the strain rate effect on flow stress and the temperature rise during impact loading were considered. These effects were evaluated with the strain rate-temperature parameter, R proposed by Bennett et al.⁵⁾. On the other hand, the uniform elongation was assumed to be independent of the strain rate and temperature. This analysis assumed transferring 90 % of plastic work to heat⁶⁾. The thermal constants used in this analysis are shown in Table 2. The inertial effect during impact loading was eliminated by quasi-static analysis in this study.

The loading rate for the Charpy specimen was 5000 mm/s and that for the 3PB specimen was 0.01 mm/s in accordance with testing standard. The value of $\sqrt{v}E$ was evaluated as an amount of work done by striker and that of δ was calculated with the load and CMOD, respectively.

3. Strength mismatch effect on toughness values

The influence of strength mismatch on $\sqrt{v}E$ and δ_{cr} was discussed using numerical analysis of the stress field. This study adopted the Weibull stress criterion for determination of the $\sqrt{v}E$ and δ_{cr} . The Weibull stress⁷⁾, σ_W was used as a driving force for brittle fracture initiation. The σ_W is given by integrating a near-tip stress over the fracture process zone V_f in the form:

$$\sigma_W = \left[\frac{1}{V_0} \int_{V_f} (\sigma_{eff})^m dV_f \right]^{1/m} \quad (2)$$

where the V_0 and m are the reference volume and material constant, respectively. V_f almost corresponds to the plastic zone near the crack tip, and σ_{eff} is an effective stress for cleavage fracture that is normally represented by the maximum principle stress. An effective stress^{8,9)} considering a random spatial distribution of microcracks was employed as σ_{eff} in Eq. (2). The selection of V_0 does not affect the transferability analysis among different specimen geometries, and the shape parameter m value has no relation with V_0 . Hence, a unit volume of 1 mm³ is often used as V_0 for convenience¹⁰⁾. This analysis also adopted $V_0=1$ mm³. The V_f for the joint specimen was defined in the part consisting of TS400, assuming that the material included crack or V-notch controls the initiation of brittle fracture and the fracture doesn't occur within TS800. It is reported that the brittle fracture initiation of steel structure components can be access by using the Weibull shape parameter, $m=10, 20$ ¹¹⁾. Accordance with this reference, $m=10$ and 20 were adopted in this study.

Fig. 3 Effect of strength mismatch on Weibull stress

It is reported that the critical Weibull stress is independent of the specimen type, size¹²⁾, loading rate¹³⁾ and strength mismatch in 3PB specimen⁴⁾. On the basis of these features, $\sqrt{E}$ and δ_{cr} for joint specimen were evaluated by the following procedure:

- (1) It is assumed that the CVN-B-specimen is fractured at $\sqrt{E}=27$ J at 0 °C, which is a required values of steels for welded structure in Japanese Industrial Standard¹⁴⁾. The $\sigma_{W,cr}$ of TS400 is calculated for each m values ($m=10, 20$) by integrating a near-tip stress over the fracture process zone when the $\sqrt{E}$ for the CVN-B-specimen is 27 J. In the case of $m=10$, $\sigma_{W,cr}$ was 1130 MPa and, in the case of $m=20$, it was 1060 MPa.
- (2) The $\sqrt{E}$ for the CVN-J-specimen is evaluated by means of Weibull stress criterion which is based on the assumption that the $\sigma_{W,cr}$ for Charpy specimen is independent of strength mismatch.
- (3) Based on the independence of $\sigma_{W,cr}$, the δ_{cr} for the CTOD-B-specimen and the CTOD-J-specimen are evaluated when their σ_W are equal to $\sigma_{W,cr}$ for the CVN-B-specimen.

The relationships between the σ_W and toughness parameters,

Fig. 4 Effect of strength mismatch on toughness ratios, $\sqrt{E}/\sqrt{E_0}$ and δ_{cr}/δ_0

calculated by using $m=20$, are shown in Fig. 3. The σ_W for joint specimen was elevated as the FL approached the V-notch or crack.

The effects of strength mismatch on $\sqrt{E}$ and δ_{cr} were investigated on the basis of Weibull stress criterion. The relationships between the toughness ratios and d are shown in Fig. 4. The ratios of $\sqrt{E}$ and δ_{cr} normalized with $\sqrt{E_0}$ and δ_{cr0} , respectively, are plotted in Fig. 4, where the $\sqrt{E_0}$ and δ_{cr0} mean $\sqrt{E}$ and δ_{cr} for the specimen of base metal, respectively. The $\sqrt{E}$ and δ_{cr} for joint specimen were lower compared with $\sqrt{E_0}$ and δ_{cr0} , respectively, although the material at the V-notch root or crack tip was the same material as the specimen of base metal. The $\sqrt{E}$ and the δ_{cr} decreased with the FL close to the V-notch or crack. In the case of $d \leq 3$ mm, the $\sqrt{E}/\sqrt{E_0}$ was smaller than δ_{cr}/δ_{cr0} . On the other hand, in the case of $d=5$ mm, the $\sqrt{E}/\sqrt{E_0}$ was larger than δ_{cr}/δ_{cr0} .

4. Strength mismatch effect on strain/temperature fields

The cause of this difference was discussed in terms of the

Fig. 5 Effect of strength mismatch on strain rate near the V-notch at brittle fracture initiation

difference of loading rate between the Charpy impact test and the CTOD fracture toughness test. Under the impact loading condition, high-speed straining increases the flow stress. The strain rate ahead of the V-notch, $\dot{\epsilon}$, at brittle fracture initiation is shown in Fig. 5. The ratio of $\dot{\epsilon}$ normalized with $\dot{\epsilon}_0$ is plotted in Fig. 5, where the $\dot{\epsilon}_0$ means the $\dot{\epsilon}$ for CVN-B- or CTOD-B-specimen at brittle fracture initiation. The $\dot{\epsilon}$ was examined at high stress field. The distance from notch and crack tip, x was 0.3 mm (Charpy specimen) and 0.1 mm (CTOD specimen), respectively. The strain rate was calculated from the increment of the equivalent plastic strain with time. In the case of $d \leq 3$ mm, the $\dot{\epsilon}$ for CVN-J-specimen was accelerated by strength mismatch. Oppositely, in the case of $d \geq 4$ mm, the strain rate for CVN-J-specimen was hardly accelerated. Because the harder material is less deformed than softer material, the plastic deformation occurred and developed in the softer material preferentially. Thus, the harder material adjacent to the V-notch provided the acceleration of strain rate for CVN-J-specimen.

Under the impact loading condition, adiabatic deformation raises the temperature of specimen. The temperature rise at brittle fracture initiation, ΔT is shown in Fig. 6. In the case of the CVN-J-specimen, the ΔT increased with increasing in d and the ΔT for CVN-B-specimen was the largest. As shown in Fig. 5, the strain rate was accelerated when FL close to V-notch and the high strain rate decreased the $\sqrt{E}$. Thus, the plastic deformation in the CVN-J-specimen was smaller than that in the CVN-B-specimen. The temperature rise for CVN-B-specimen increased because the plastic deformation was large. The temperature rise decreases the flow stress. In this study, it was assumed that the critical Weibull stress was independent of temperature. Thus, this increase in temperature rise for CVN-B-specimen expanded the difference of the $\sqrt{E}$ between CVN-B- and CVN-J-specimen.

In the case of fracture toughness test, the strain rate was affected by the strength mismatch, as shown in Fig. 5. The acceleration was smaller than that for the Charpy specimen. The

strain rate for CTOD-J-specimen is about 5×10^{-4} /s. Therefore, the elevation of flow stress by acceleration of strain rate was small. Figure 6 shows that temperature rise were negligibly small, and the strength mismatch didn't affect the temperature rise. The flow stress near crack-tip was affected only by plastic constraint. On the other hand, in the case of the Charpy impact test the flow stress was affected by acceleration of strain rate and suppression of temperature rise, besides plastic constraint. Above all, because of the difference of the loading rate, the sensitivities of the $\sqrt{E}$ and δ_{cr} on strength mismatch were different from each other.

In the case of d was 5 mm, the δ_{cr}/δ_{cr0} was smaller than $\sqrt{E}/\sqrt{E_0}$. As shown in the Fig. 3, the Weibull stress for CVN-J-specimen was hardly elevated. On the other hand, that for CTOD-J-specimen was elevated compared with CTOD-B-specimen. In the case of the CVN-J-specimen, the plastic constraint, the effects of strength mismatch on strain rate and the temperature rise were small. On the other hand, in the case of CTOD-J-specimen, the plastic constraint was occurred when d was large.

Conclusion

In this study, the difference between the sensitivity of Charpy absorbed energy and critical CTOD to strength mismatch was investigated, on the basis of the Weibull stress criterion for brittle fracture. It was found that the Charpy absorbed energy was more affected by strength mismatch than critical CTOD when the fusion line was close to the V-notch and crack. The cause of this effect of strength mismatch on toughness values was discussed in terms of the difference of the loading rate between the Charpy impact test and CTOD fracture toughness test. In the case of the Charpy specimen subjected to impact loading, the strain rate for CVN-J-specimen, especially $d \leq 3$ mm, was accelerated by strength mismatch. Because of this, the stress field for the CVN-J-specimen was elevated, and the $\sqrt{E}$ for CVN-J-specimen was smaller than that for CVN-B-specimen. Then, the temperature rise for CVN-J-specimen decreased with the FL close to the V-notch. In this study, it was assumed that the $\sigma_{W,cr}$ was independent of the strain rate and temperature. On the other hand, the flow stress depends on them. Accordingly, because of the acceleration of strain rate, especially $d \leq 3$ mm, and the suppression of temperature rise for the CVN-J-specimen by strength mismatch, the $\sqrt{E}$ for CVN-J-specimen was smaller than CVN-B-specimen. On the other hand, in the case of the CTOD fracture toughness specimen subjected to static loading, the effects of strength mismatch on strain rate and temperature rise

Fig. 6 Effect of strength mismatch on temperature rise near the V-notch at brittle fracture initiation

are negligibly small. Thus, because of the difference of the loading rate, the sensitivities of Charpy absorbed energy and critical CTOD to strength mismatch were different from each other. This result implies that when considering the correlation between the Charpy absorbed energy and fracture toughness value in welds, the difference between the sensitivity of the Charpy absorbed energy and fracture toughness value to strength mismatch should be taken into account.

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