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ABSTRACT

Overview of the quantitative evaluation procedure of strain rate and temperature effects on fracture toughness proposed by the authors is introduced. Important concept of former researches is that the fracture toughness is a function of the strain rate - temperature parameter (R), which enables to unify both strain rate and temperature effects for the mechanical properties of materials. Using this knowledge, the equivalent temperature shift values at arbitrary strain rate from static loading condition are proposed.

INTRODUCTION

It is well known that the fracture toughness of steels is affected by strain rate and temperature. Fracture toughness under high strain rate shows lower value than under static loading condition and fracture toughness under low temperature shows lower value than under room temperature. In general, strain rate acting on various structures is three or four order faster than one under static fracture toughness test. Table 1 [1] shows examples of strain rate acting on structural elements at in-service operation. Besides, in-service temperature conditions of welded steel structures are wide variety. Then, it is very important to quantify strain rate and temperature effects on the fracture toughness of steels.

Overview of the quantitative evaluation procedure of the strain rate and temperature effects on fracture toughness proposed by authors [2] [3] [4] is introduced in this paper. The strain rate - temperature parameter (R), which enables to unify both effects of yielding and plastic deformation occurring under the rate process, is applied to this procedure. Stress versus strain relation under arbitrary strain rate and temperature conditions as a function of R parameter were established. As the results of the thermal elastic-plastic FE analysis for fracture toughness tests, which implement above mentioned stress versus strain relation, it was confirmed that the fracture toughness is a function of R parameter in the fracture process zone. Using this knowledge, the equivalent temperature shift values under arbitrary strain rate from static loading condition are proposed.

TABLE 1. EXAMPLES OF THE STRAIN RATE ACTING ON STRUCTURAL ELEMENT AT IN-SERVICE OPERATION [1].

Type of structures	Type of loading	strain rate [s^{-1}]
Horizontal brace of semi- submergible structures	Waves	2.0×10^{-4}
	Collision	$10^{-3} \sim 10^{-2}$
Liquid cargo ship	Sloshing	10^{-4}
Hull	Slamming	10^{-3}

OVERVIEW OF THE EVALUATION PROCEDURE OF THE STRAIN RATE AND TEMPERATURE EFFECT ON FRACTURE TOUGHNESS [2] [3] [4]

Stress versus strain relations as a function of *R* parameter

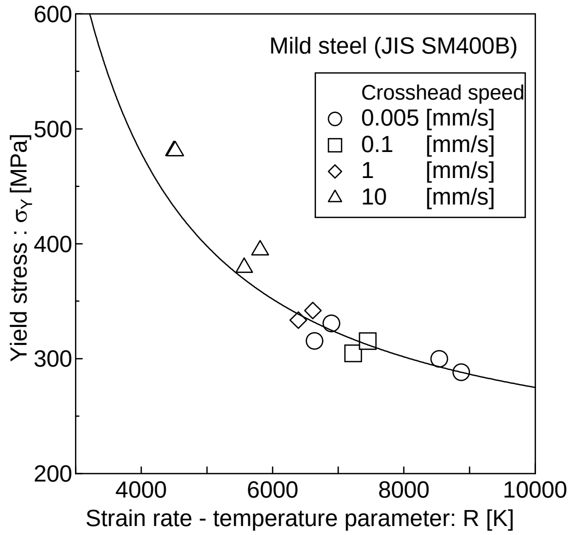
It is well known that the yield stress (or 0.2% proof stress) of steels increases as temperature decreases and as strain rate increases. By applying the strain rate - temperature parameter (R) which prescribes the activation energy under the rate process of plastic deformation [5] and defined by Eq.(1), the yield stress of steels under arbitrary strain rate and temperature conditions can be described as a function of R parameter, see Fig.1.

$$R = T \ln\left(10^8/\dot{\varepsilon}\right), \tag{1}$$

$$\sigma_Y = A \exp\left(B/R\right), \tag{2}$$

where

T: absolute temperature [K],
σ_Y: yield stress of materials,
$\dot{\varepsilon}$: strain rate [s^{-1}] and
A, B: material constants.



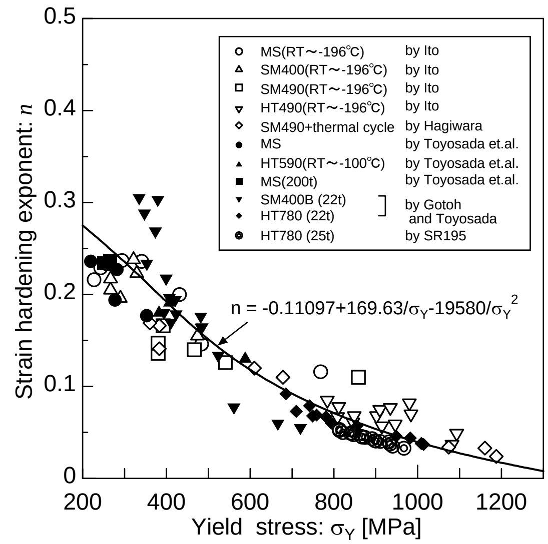


FIGURE 1. AN EXAMPLE OF RELATIONSHIP BETWEEN *R* PARAMETER AND YIELD STRESS OF MAERIALS.

FIGURE 2. RELATIONSHIP BETWEEN YIELD STRESS OF WELDED STRUCTURAL STEELS AND STRAIN HARDENING EXPONENTS.

Assuming the constitutive equation of a materials is expressed by the *n*-th power work hardening shown in Eq. (3), it is also confirmed that strain hardening exponent (*n*) depends on the yield stress σ_Y at static loading conditions. The *n* value could be approximated as a function of σ_Y and shown in Eq. (4), see Fig.2.

$$\sigma = F\varepsilon^n \tag{3}$$

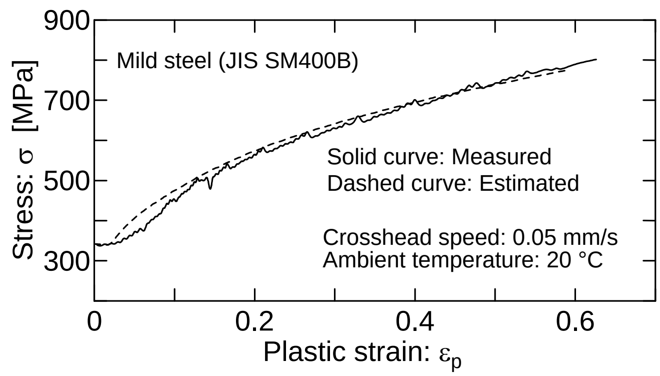
$$n = -0.11097 + 169.63/\sigma_Y - 19580/\sigma_Y^2 , \tag{4}$$

where the unit of σ_Y is MPa. The coefficient *F* in Eq. (3) is given as $\sigma_Y\,(E/\sigma_Y)^n$, where *E* is Young's modulus.

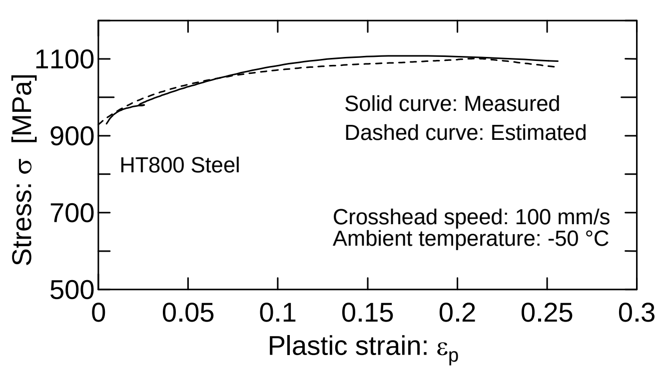
The stress versus strain relations after the yielding under arbitrary strain rate and temperature conditions can be estimated by the following procedure.

1. The value of *R* parameter at the current conditions is obtained by Eq. (1) and loading conditions.
2. Current values of σ_Y and *n* are obtained by Eqs. (2) and (4).
3. Current stress value can be calculated by Eq. (3).

Figure 3 shows examples of comparison between measured and estimated stress versus strain diagrams under arbitrary strain rate and ambient temperatures, where measured strain rate and temperature including the plastic work during the loading in every moment were used in order to estimate the diagrams. This results indicate that the *R* parameter under dynamic loading condition plays the same role as a temperature under static loading condition for the stress and strain behavior.



(a) Mild steel (JIS SM400B)



(b) HT800 Steel

FIGURE 3. COMPARISON OF MEASURED STRESS VERSUS STRAIN DIAGRAMS WITH MEASURED ONES.

Relationship between fracture toughness and *R* parameter in the fracture process zone

To discuss the strain rate and temperature effect by *R* parameter, the distributions of *R* parameter near a crack tip in the fracture toughness tests under arbitrary loading conditions were investigated by the thermal elastic-plastic finite element analysis into which the stress versus strain relations described by *R* parameter and mentioned above was implemented. Figure 4 shows a calculation result of *R* parameter distribution in IDNZ which is the fracture process zone defined by Rice et al. [6] at a moment of loading process.

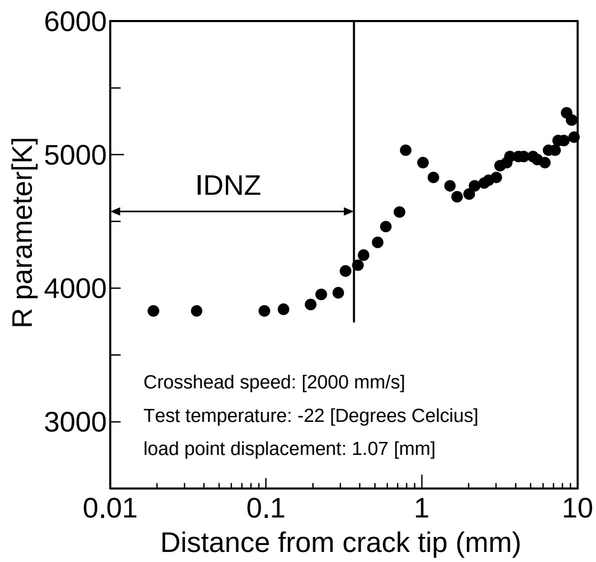
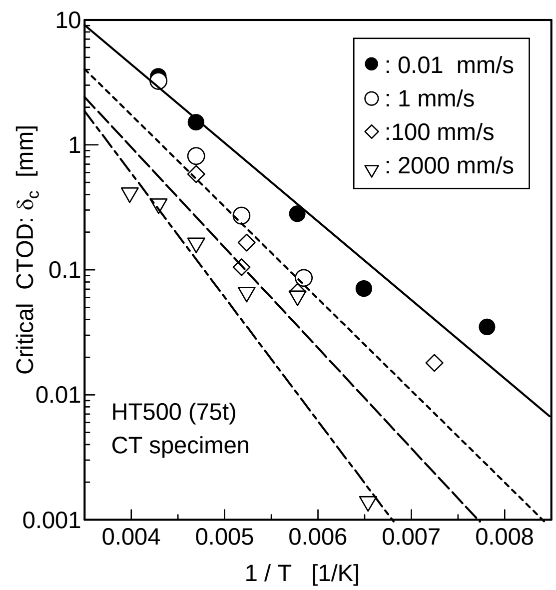


FIGURE 4. AN EXAMPLE OF R PARAMETER DISTRIBUTION IN THE FRACTURE PROCESS ZONE.

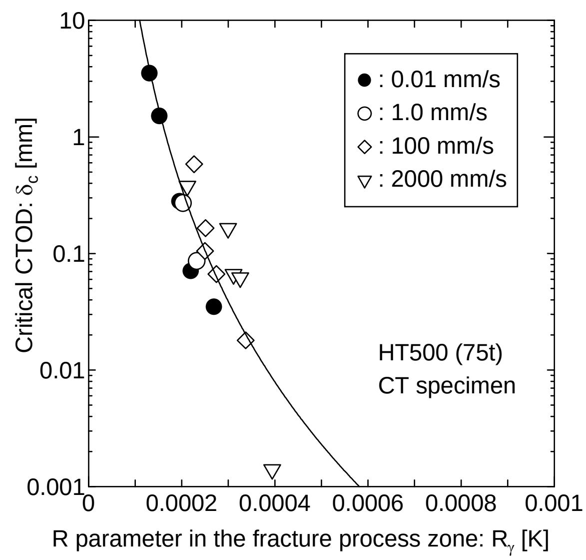
It is confirmed that *R* parameter in the fracture process zone keeps some constant value at every moment. In the following, this constant value of *R* parameter in the fracture process zone is described by R_γ. This situation might be caused by the synergetic effect of the temperature rise due to plastic work and the strain rate gradient in the vicinity of a crack tip. This result indicates that the precise fracture initiation point should not be identified to evaluate the strain rate and temperature effect on fracture toughness, because the fracture might occur in the region of fracture process zone where R_γ keeps a constant at an arbitrary moment.

Since the fracture toughness under static loading condition is a function of temperature and the *R* parameter under dynamic loading condition plays the same role as a temperature under static condition, it was expected that the univocal relationship between R_γ and the fracture toughness might be established as the material characteristics.

Figure 5 is an example of the relationship between R_γ and the fracture toughness in the fracture toughness tests under arbitrary loading speed (0.01~2,000mm/s) and ambient temperature (-145~22°C) conditions. The value of R_γ at the fracture occurrence was calculated by dynamic thermal elastic-plastic FE analysis which implements the stress versus strain relation mentioned above. Local temperature rise due to the plastic work can be considered by this FE analysis and the values of R_γ in Fig.5 were given by considering the effect of temperature rise in the vicinity of a crack tip due to plastic work. Effect of the thermal conductivity in the specimen was also considered to calculate the value of R_γ during the loading.



(a) TEMPERATURE VERSUS FRACTURE TOUGHNESS



(b) R PARAMETER IN THE FRACTURE PROCESS ZONE VERSUS FRACTURE TOUGHNESS

FIGURE 5. RELATIONSHIP BETWEEN FRACTURE TOUGHNESS AND THE VALUE OF R PARAMETER IN THE FRACTURE PROCESS ZONE.

It was confirmed that the unstable fractures under different strain rate and temperature conditions is occurred at the same R_γ conditions.

EQUIVALENT TEMPERATURE SHIFT VALUES AT ARBITRARY STRAIN RATE FROM STATIC LOADING CONDITION

Considering the relationship between R_γ and fracture toughness at arbitrary strain rate, the equivalent temperature shift value, which the same fracture toughness is achieved at the static loading condition, can be obtained by the following equation.

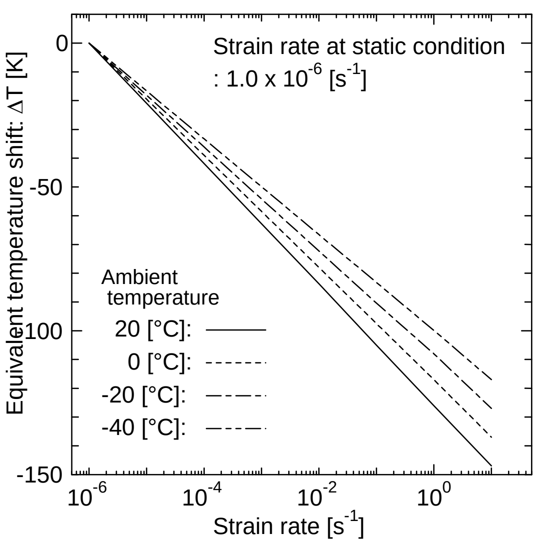
$$\Delta T = T \ln\left(\dot{\varepsilon}_{\text{static}}/\dot{\varepsilon}_a\right) \Big/ \ln\left(10^8/\dot{\varepsilon}_{\text{static}}\right), \tag{4}$$

where

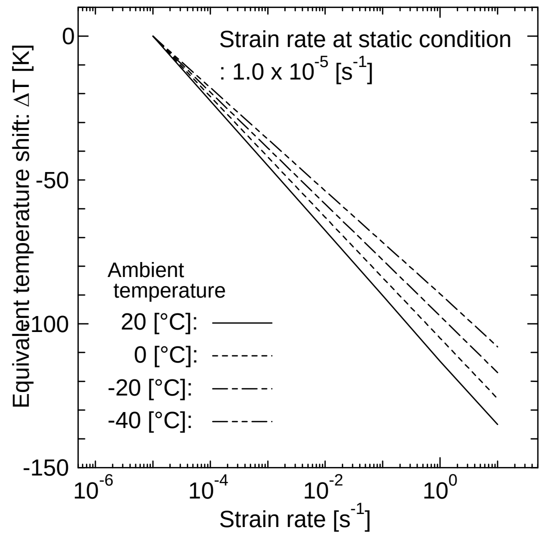
- ΔT: temperature shift value [K],
- $\dot{\varepsilon}_{\text{static}}$: strain rate [s^{-1}] at the static loading condition and
- $\dot{\varepsilon}_a$: strain rate [s^{-1}] at reference condition.

Parametric study was performed to investigate ΔT values under some strain rate and ambient temperature conditions. Three strain rates was set as the static loading conditions in this numerical studies and these results are shown in Fig.6.

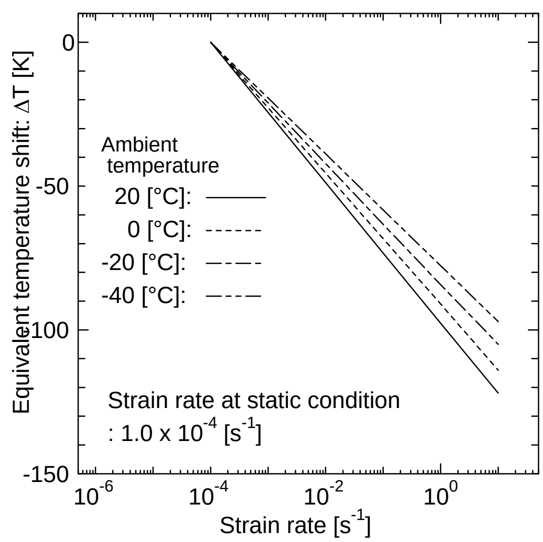
It is confirmed from these figures that the equivalent temperature shift from the static loading condition is increasing with increasing applied strain rate. It is considered that the equation of ΔT defined as Eq. (E11-2) in Ref. [1] corresponds that the strain rate at static load is equal to 1.0 x10^{-4} [s^{-1}].



(a) STATIC STRAIN RATE 1.0X10^{-6} [S^{-1}]



(b) STATIC STRAIN RATE 1.0X10^{-5} [S^{-1}]



(c) STATIC STRAIN RATE 1.0X10^{-4} [S^{-1}]

FIGURE 6. EQUIVALENT TEMPERATURE SHIFT VALUES AT ARBITRARY STRAIN RATE FROM STATIC LOADING CONDITIONS.

By considering the amount of equivalent temperature shift, fracture toughness under arbitrary strain rate and ambient temperature can be approximately estimated by the following procedure.

1. Conducting the fracture toughness tests under some ambient temperatures and the static loading condition and obtaining the relationship between temperature (T) and fracture toughness (δ_c^{static}).

2. Calculating the equivalent temperature shift ΔT at the reference strain rate ($\dot{\varepsilon}_a$) and temperature (T) by Eq. (4).
3. Fracture toughness (δ_c (T)) at the reference loading condition is obtained as follows.

$$\delta_c\left(T\right)\approx\delta_c^{\text{static}}\left(T+\Delta T\right) \quad (5)$$

It should be noted that the effect of local temperature rise near a crack tip due to plastic work is ignored in this procedure. It is recommended that the thermal elastic-plastic finite element analysis is applied to consider the effect of local temperature rise near a crack tip, especially very high loading speeds, e.g. impact loadings.

CONCLUDING REMARKS

Overview of the quantitative evaluation procedure of strain rate and temperature effects on fracture toughness and the approximate estimation procedure of fracture toughness under arbitrary strain rate and ambient temperature condition is introduced in this paper. Basic concept of this method is that the fracture toughness is a function of R parameter in the fracture process zone. It should be noted that the effect of local temperature rise near a crack tip due to plastic work is ignored in this procedure.

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