Cleavage Fracture Toughness of SA508 Gr.4N High Strength Low Alloy Steel with Different Phase Fraction

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1. Introduction

Materials for reactor pressure vessel (RPV) are required to have good mechanical properties to endure the severe operating conditions inside the reactor. Various researches have focused on improving mechanical properties by the controlling the heat treatment process of commercial SA508 Gr.3 RPV steel [1-3]. Some studies for identifying new material with high strength and toughness for larger capacity and longer lifetime of reactor are being performed [4, 5]. SA508 Gr.4N low alloy steel may be a promising RPV material due to its excellent mechanical properties from its tempered martensitic microstructure.

Recently, some research showed that F/M steel composed of the tempered martensite has a steeper temperature dependency of the fracture toughness than the master curve expression [6]. We have also focused on the steep transition properties of tempered martensitic SA508 Gr.4N steel in previous research [7]. However, it has not yet confirmed that the transition behavior including temperature dependency with tempered martensite fraction.

This investigation aims to evaluate the relationship between cleavage fracture toughness and tempered martensite fraction for SA508 Gr.4N low alloy steel. For this purpose, the model alloys were prepared by controlling the cooling rate from the austenitization temperature. The cleavage fracture toughness was characterized in transition temperature region by 3-point bending tests. Based on the test results and a stress distribution near crack tip calculated in FE analysis, the relationship between the carbide size distributions and the transition properties are analyzed.

2. Experimental Procedure

The chemical composition of tested material is shown in Table 1. The model alloys were austenitized for 2h at 880^{o}C followed by cooling in furnace, air and iced water to produce different tempered martensite fraction, and then they were tempered for 10h at 660^{o}C. The measured cooling rates are 0.05, 0.47, and 16^{o}C/s, respectively. Fracture toughness tests were carried out in 3-point bending with the standard pre-cracked Charpy (PCVN) specimens (10x10x55mm), in which the initial fatigue crack length was about 5mm. The test temperature was controlled within ±0.5^{o}C in an insulated chamber with a regulated liquid nitrogen flow.

The stress distributions near crack tip of PCVN specimens of model alloys were calculated by FEM analysis using ABAQUS 6.10.

Table 1. The chemical composition of test material.

	C	Ni	Cr	Mo	Mn	P
Model alloy	0.19	3.59	1.79	0.49	0.30	0.002

3. Results and Discussion

The specimens cooled at 16^{o}C/s (WQ) and 0.05^{o}C/s (FC) show predominantly the tempered martensitic and the tempered bainitic microstructures, respectively. However, the specimen cooled at 0.47^{o}C/s (AC) shows in the mixed-structure of tempered martensite and bainite. In the results of dilatometric analysis on the phase fraction, the volume fractions of martensite in the specimens cooled at 16, 0.47 and 0.05^{o}C/s are about 93%, 67% and less than 1%, respectively.

The standard master curves in accordance with ASTM E1921-11 together with the measured K_{Jc} values for different phase fraction are presented in Fig. 2. The reference temperatures, T_0, for FC, AC, and WQ are -126.2, -134.5, and -153.0^{o}C, respectively. T_0 values decrease with decreasing the phase fraction of tempered martensite. The exponential fitting for the measured K_{Jc} values was performed to confirm the temperature dependency of K_{Jc} values. The exponential parameters related to the curve shape are 0.040(WQ), 0.034(AC) and 0.026(FC). The steepness of K_{Jc} evolution with temperature increases with increasing the tempered martensite fraction.

The local principal stress at the cleavage initiation site determined from the stress distribution near precrack tip calculated by FEM analysis, depending on the yield stress and strain hardening exponent (n), and the critical initiation distance (CID). The CID is the distance from a crack tip to a cleavage initiation site on the fracture surface of specimen. The σ_{yy} was taken as the principal stress at CID on the stress distribution curve, and the critical carbide size for cleavage fracture was calculated from Eq. 1 with the determined σ_{yy}.

$$\sigma_{yy} = [\frac{\pi E \gamma_p}{(1-\nu^2) r_c}]^{1/2} \quad (1)$$

The critical carbide size, r_c are 0.20μm, 0.19μm, and 0.16μm for FC, AC, and WQ, respectively. The microcracks formed in carbides larger than the r_c are could propagate into the ferrite matrix.

The fraction of carbides larger than a certain size could be expressed by the Weibull function as follows [8]:

$$P(r > r_0) = \exp(-r_o (r_0 - r_u))^m \quad (2)$$

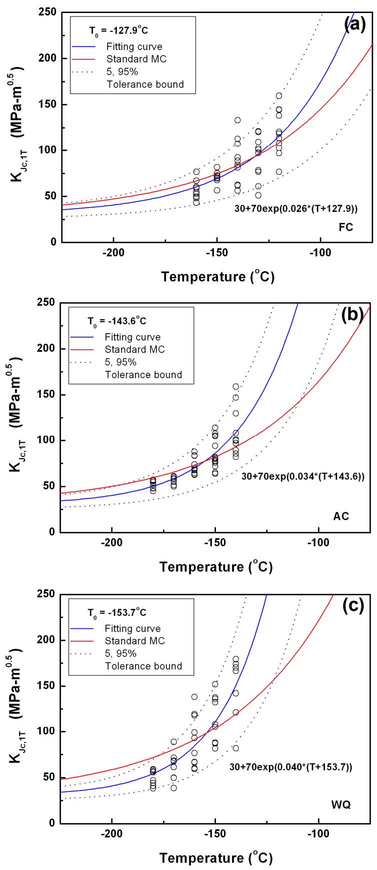

Fig. 1. Standard master curves and fitting curves together with the measured K_{Jc} values of (a) FC, (b) AC and (c) WQ.

where $P(r>r_0)$ is the probability of discovering carbides larger than r_0, r_u is the resolution limit, r_o is the Weibull parameter, and m is the shape factor of the distribution. Fig. 2 shows the carbide size distributions with the Weibull model. It was reported that the cleavage fracture toughness and the probability of discovering the weakest site for cleavage fracture, such as carbide and inclusion, have linear relation [8, 9]. Therefore, T_0 and the $P(r > r_c)$ are correlated as below:

$$T_0 \propto -\ln(K_{Jc}) \propto \ln(P(r > r_c)) \propto (r_c - r_u)^m \quad (3)$$

The relationship between the T_0 value and r_c are shown in Fig. 3. T_0 and $(r_c\text{-}r_u)^m$ satisfied the linear relationship well. Consequently, higher fraction of the tempered martensite results in improving the transition property by reducing the probability of discovering carbide larger than the critical size in front of crack tip.

5. Summary

In this work, the effects of phase fraction of tempered martensite on the transition behavior of SA508 Gr.4N low alloy steels were assessed. The better transition properties and steeper temperature dependency of the K_{Jc} values observed in higher tempered martensite fraction. The critical carbide sizes required for cleavage fracture were determined from a local principal stress at a cleavage initiation site by using a stress distribution near crack tip calculated in FE analysis and a cleavage initiation distance measured on fracture surface. Quantitative analysis of carbide size shows that the increase of tempered martensite fraction reduce the probability of discovering carbides larger than a critical size and the steepness of temperature dependency of the K_{Jc} values is strongly related to a variation of critical carbide size with test temperature.

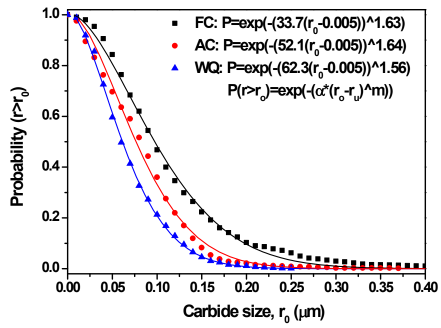

Fig. 2. The probability of discovering carbide larger than certain size determined from the Weibull function.

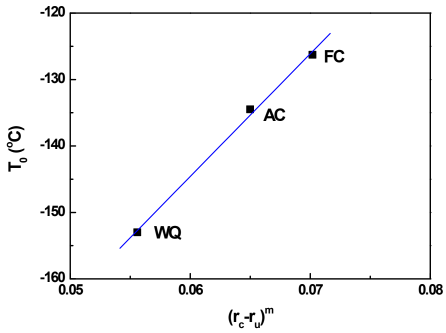

Fig. 3. The relationship between reference temperature, T_0, and critical carbide size.

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