Fracture Toughness in Transition Temperature Region with Cooling Rate for SA508 Gr. 4N Model Alloys

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1. Introduction

Materials for reactor pressure vessel (RPV), which is the key component in the determination of the life span and safety margin of reactors, are required to have enough mechanical properties to endure the high pressure inside the reactor. Various studies have focused on improving mechanical properties by the controlling the heat treatment process of commercial RPV steel, SA508 Gr.3 Mn-Mo-Ni low alloy steel [1-3]. On the other hand, some researches for identifying new material with high strength and toughness for larger capacity and longer lifetime of reactor are being conducted [4, 5]. SA508 Gr.4N Ni-Cr-Mo low alloy steel may be a candidate RPV material due to its excellent mechanical properties from its tempered martensitic microstructure.

Wallin observed that the temperature dependency of fracture toughness is not sensitive to the chemical composition, heat treatment, and irradiation for ferritic steels [6]. This result led to the concept of a universal shape in the median toughness-temperature curve for all 'ferritic steels'. Recently, some researches showed that F/M steel composed of the tempered martensitic microstructure has steeper temperature dependency of the measured fracture toughness than the prediction in the master curve [7, 8]. We also focused on the steep transition properties of SA508 Gr.4N low alloy steel with tempered martensitic structure in previous research [9]. However, it has not yet confirmed whether that the transition properties including temperature dependency vary with phase fraction of tempered martensite.

In this study, the effect of fraction of tempered martensite on the fracture toughness transition behavior in SA508 Gr.4N was assessed by controlling cooling rate after austenitization. The relationship between phase fraction and the fracture toughness variation with temperature in the transition region was analyzed. Also, the tendencies were compared with the prediction in the standard master curve and the results from other RPV steels.

2. Experimental Procedure

The materials used in this work are a model alloy in which the chemical composition is in the middle range of the specification of SA508 Gr.4N steel as shown in Table 1. The model alloys were austenitized for 2h at 880°C followed by cooling in furnace, air and iced water to produce different phase fraction of tempered martensite, and then they were tempered for 10h at 660°C. The measured cooling rates are 0.05, 0.47, and 16°C/s, respectively. The samples were etched by 3% nital and then microstructure was observed by an optical microscope. 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°C in an insulated chamber by PID controller equipped with a regulated liquid nitrogen flow.

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°C/s (WQ) and 0.05°C/s (FC) appear predominantly the tempered martensitic and the tempered bainitic microstructures, respectively. However, the microstructure of the specimen cooled at 0.47°C/s (AC) appear 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 which were cooled at 16, 0.47 and 0.05°C/s are about 93%, 67% and less than 1%, respectively.

Fig. 2 shows the standard master curves together with the K_{Jc} values of model alloys. The exponential fitting for the measured K_{Jc} values from individual cooling conditions was conducted to confirm the K_{Jc} evolution with temperature. The steeper dependencies of K_{Jc} values with temperature than that predicted in the standard master curve are generally indicated in all cooling conditions. The exponential parameters related to the curve shape are 0.040(16°C/s of cooling rate), 0.034(0.47°C/s) and 0.026(0.05°C/s). Fig. 3 shows the reference temperature, T_0, and the exponential parameter representing the temperature dependency of the K_{Jc} values with the tempered martensite fraction. T_0 values drop with decreasing the phase fraction of tempered martensite in model alloy. However, T_0 values determined from the fitting curves may have closer relationship with the fraction in comparison with T_0 values determined from the standard master curves. The exponential constants have nearly linear relationship with the fraction of tempered martensite. In the case of model alloy composed of about 93% tempered martensite, the steepness of transition in the measured K_{Jc} values is same with the results of F/M steel from

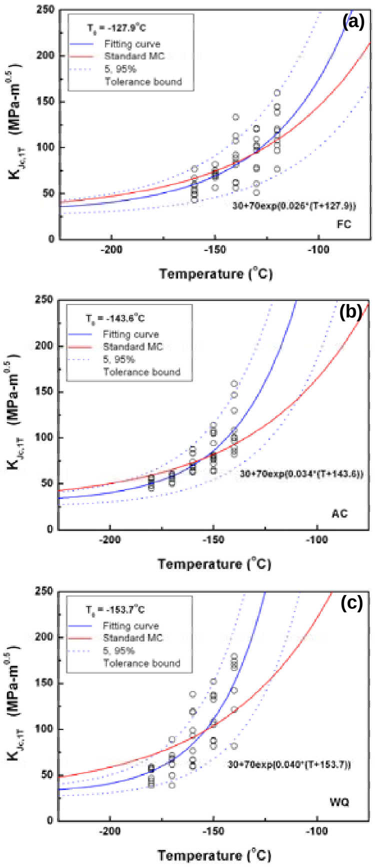

Fig. 1. Standard master curves and fitting curves together with the measured K_{Jc} values of KL4-Ref cooled at (a) 0.05°C/s, (b) 0.47°C/s and (c) 16°C/s.

literature [7]. On the other hand, the model alloy composed of fully bainitic microstructure shows the steeper temperature dependency of the K_{Jc} values than the prediction of standard master curve and the fitting result for the measured K_{Jc} values in Gr.3. It was inferred that the variation of K_{Jc} evolution with the phase fraction and materials was resulted from the difference in tensile properties with temperature. The additional analysis on the variation of stress concentration near crack-tip and the critical fracture stress with the phase fraction and material is presently ongoing.

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 results of microstructural observations and dilatometric analysis show the tempered martensite fraction of about 93%, 66% and less than 1% in cooling rate of 16, 0.47 and 0.05°C/s, respectively. In the results of fracture toughness tests, the K_{Jc} evolution with a temperature in all cooling conditions indicates the steeper evolutions than that predicted in the standard master curve. The steeper temperature dependency of K_{Jc} is observed with the higher fraction of tempered martensite. In addition, T_0 values determined from the fitting curves may have closer relationship with the fraction in comparison with T_0 values determined from the standard master curves.

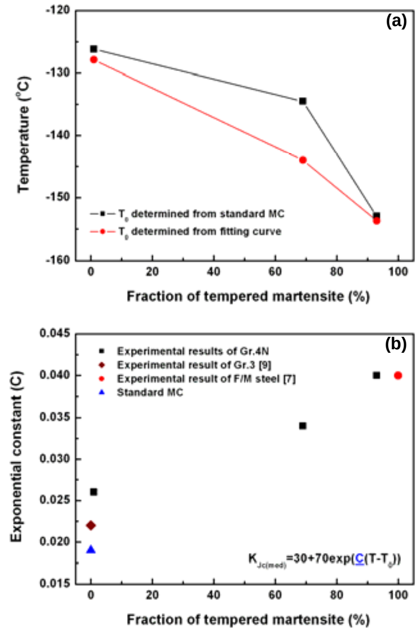

Fig. 2. Variation of transition properties with the tempered martensite fraction: (a) T_0 values and (b) exponential constants.

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REFERENCES

[1] Y. S. Ahn et al, Nucl. Eng. Design 194 (1999) 161
[2] Y. R. Im et al, J. Nucl. Mater. 297 (2001) 138
[3] Y. S. Ahn et al, J. Kor. Inst. Met. & Mater. 38 (2000) 1309
[4] B. S. Lee et al, Int. J. Press. Ves. Piping 85 (2008) 593
[5] K. H. Lee et al, Mater. Sci. Eng. A 527 (2010) 3329
[6] ASTM E1921-09c, 2009
[7] R. Bonade et al, J. Nucl. Mater. 367-370 (2007) 581
[8] E. Lucon, J. Nucl. Mater. 367-370 (2007) 575
[9] K. H. Lee et al, J. Nucl. Mater. 403 (2010) 68