Transactions of the Korean Nuclear Society Autumn Meeting
Jeju, Korea, October 21-22, 2010

Effects of Phase Fraction on Temperature Dependency of Fracture Toughness in Transition Temperature Region in SA508 Gr. 4N Ni-Mo-Cr Low Alloy Steels

Ki-Hyoung Lee[a], Min-Chul Kim[b], Bong-Sang Lee[b], Dang-Moon Wee[a]
[a]*KAIST, Department of Materials Science & Engineering, Guseoung-dong, Yuseong-gu,Daejeon, 305-701, Korea*
[b]*KAERI, Nuclear Material Research Div., 150 Deogjin-dong, Yuseong-gu, Daejeon, 305-353, Korea*

1. Introduction

The Reactor Pressure Vessel (RPV) is the main component in determining the lifetime of nuclear power plants because it is subject to the aging phenomenon of irradiation embrittlement and there is no practical method for replacing that component. For materials used for the RPV, sufficient strength and toughness are required to prevent failure against the severe operating conditions and the aging degradation of materials [1, 2]. SA508 Gr.4N Ni-Mo-Cr low alloy steel, in which Ni and Cr contents are higher than in conventional RPV steels, may be a promising RPV material with the improved strength and toughness 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 [3, 4]. This result led to the concept of a universal shape in the median toughness-temperature curve for all 'ferritic steels'. However, there are some doubts about the universal shape in the ASTM master curve for the tempered martensitic steels, such as Eurofer97 [5-7]. It was also reported that the fracture toughness increased discontinuously when the phase fraction of the tempered martensite was over a critical fraction in the heat affected zones of SA508 Gr.3 [8]. Therefore, it may be necessary to evaluate the changes of transition behavior with microstructures of steel.

In this study, the effects phase fraction of tempered martensite controlled by a cooling rate on the transition behavior of SA508 Gr.4N low alloy steels was evaluated. Additionally, the relationship between the variations of yield strength with the temperature and fracture stress in a local approach was discussed.

3. Experimental Procedure

The materials used in this work are a reference 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 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
KL4-Ref	0.19	3.59	1.79	0.49	0.30	0.002

3. Results and Discussion

Fig. 1 shows the measured cooling curves of KL4-Ref plotted with continuous cooling transformation (CCT) diagram of HY-80 steel [9], which has a similar chemical composition (0.19% C, 3.30% Ni, 1.78% Cr, 0.50% Mo, 0.30% Mn, 0.007% P) to that of Gr.4N. As indicated in the diagram, the specimen quenched by a cooling rate of 16°C/s should have an almost fully martensitic microstructure. On the other hand, the specimen cooled by a rate of 0.47°C/s was expected to have a mixture of tempered bainite and martensite, and the cooled one by a rate of 0.05°C/s may have almost fully bainite.

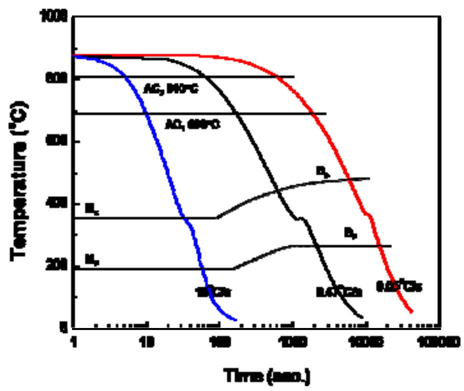

Fig. 1. Cooling curve profiles for the different cooling rates plotted with the CCT diagram of SA508 Gr.4N steels.

Optical micrographs of the specimens confirm the microstructure as shown in Fig. 2. The micrographs of steels showed the prior austenite grain boundaries and the packets of parallel lath. The specimens cooled at 16°C/s and 0.05°C/s appeared predominantly the tempered martensitic and the tempered bainitic microstructures, respectively. However, the microstructure of the specimen cooled at 0.47°C/s appeared 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^{o}C/s were about 92%, 66% and less than 10%, respectively.

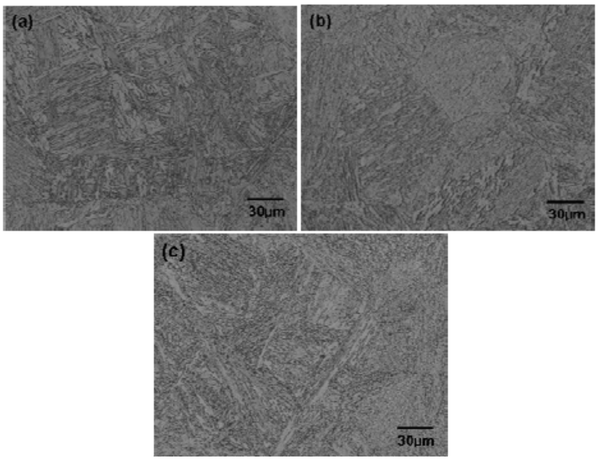

Fig. 2. Optical micrographs of KL4-Ref cooled at (a) 16^{o}C/s, (b) 0.47^{o}C/s and (c) 0.05^{o}C/s.

Fig. 3 shows the standard master curves together with the K_{Jc} values of KL4-Ref quenched at 16^{o}C/s. The exponential fitting for K_{Jc} values from individual cooling conditions was undertaken to confirm the K_{Jc} evolution with temperature. To minimize changes in the basic form of the master curve expression, only the exponential coefficient related to the curve shape was adjusted, while the other parameters (30 and 70) related to the position of the curve on the temperature axis were not adjusted. The results showed that the steeper dependencies of K_{Jc} values with temperature than that predicted in the standard master curve were generally indicated in all cooling conditions. The exponential parameters related to the curve shape were 0.040(16^{o}C/s of cooling rate), 0.034(0.47^{o}C/s) and 0.027(0.05^{o}C/s). Those reflected that the steeper temperature dependency of K_{Jc} was indicated with the higher volume fraction of tempered martensite. It was inferred that the steeper K_{Jc} evolution in tempered martensite was resulted from the difference in variation of tensile properties with temperature. Therefore, the additional analysis on the relationship between the variation of yield strength with temperature and fracture stress in local approach is presently ongoing.

5. Summary

This work focused on the effects of phase fraction of tempered martensite on the transition behavior of SA508 Gr.4N low alloy steels. As predicted from the cooling curves plotted in the CCT diagram, the results of microstructural observations and dilatometric analysis showed the volume fraction of tempered martensite of about 93%, 66% and less than 10% in cooling rate of 16, 0.47 and 0.05^{o}C/s, respectively. In the results of fracture toughness tests, the K_{Jc} evolution with a temperature in all cooling conditions indicated the steeper evolutions than that predicted in the standard master curve. In addition, the steeper temperature dependency of K_{Jc} was indicated with the higher volume fraction of tempered martensite.

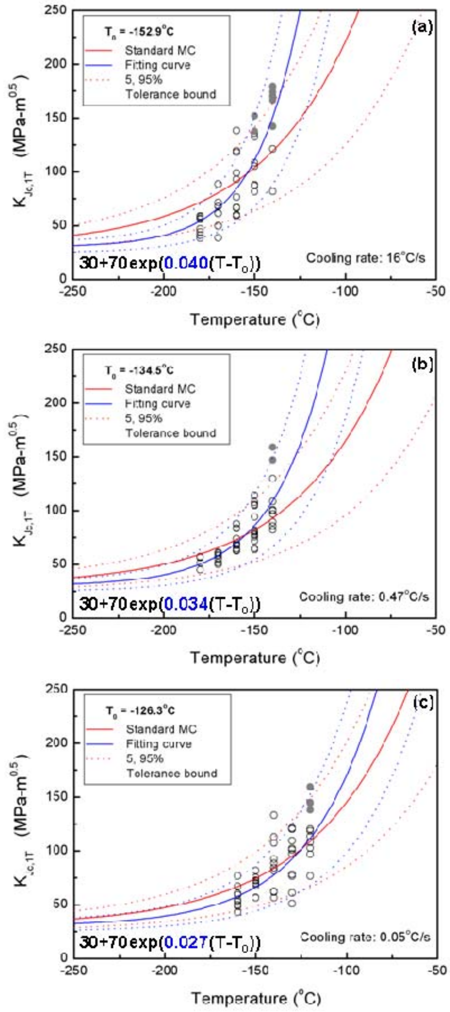

Fig. 3. Standard master curves and fitting curves together with the K_{Jc} values of KL4-Ref cooled at (a) 16^{o}C/s, (b) 0.47^{o}C/s and (c) 0.05^{o}C/s

Acknowledgement

This work was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

REFERENCES

[1] S. G. Druce et al, Nucl. Energy 9 (1980) 347
[2] K. Suzuki, J. Nucl. Mater. 108&109 (1982) 443-450
[3] K. Wallin, Eng. Frac. Mech. 19 (1984) 1085
[4] K. Wallin, Eng. Frac. Mech. 22 (1985) 149
[5] P. Muller et al, J. of Nucl. Mater. 386-388 (2009) 323
[6] R. Bonade et al, J. of Nucl. Mater. 367-370 (2007) 581
[7] E. Lucon, J. of Nucl. Meter. 367-370 (2007) 575
[8] H. S. Shin et al, J. Kor. Inst. Met. & Mater. 37 (1999) 1260