Transactions of the Korean Nuclear Society Spring Meeting
Pyeongchang, Korea, May 27-28, 2010

Ductile-Brittle Transition Behavior in Tempered Martensitic SA508 Gr. 4N Ni-Mo-Cr Low Alloy Steels for Reactor Pressure Vessels

Ki-Hyoung Lee[a], Min-Chul Kim[b], Bong-Sang Lee[b], Dang-Moon Wee[a]
[a]*KAIST, Advanced High Temperature Materials Lab., 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

Reactor pressure vessels (RPVs) operate under severe conditions of elevated temperature, high pressure, and irradiation. Therefore, a combination of sufficient strength, toughness, good weldability, and high irradiation resistance are required for RPV materials [1, 2]. SA508 Gr.4N low alloy steel, which has higher Ni and Cr contents than those of commercial RPV steel, Gr.3 steel, is considered as a candidate material due to its excellent mechanical properties from tempered martensitic microstructure.

The ferritic steels such as Gr.3 and Gr.4N low alloy steels reveal a ductile-brittle transition and large scatters in the fracture toughness within a small temperature range. Recently, there are some observations of the steeper transition behavior in the tempered martensitic steels, such as Eurofer97 than the transition behavior of commercial RPV steels [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 a microstructure for the tempered martensitic SA508 Gr.4N low alloy steel.

In this study, the fracture toughness for SA508 Gr.4N low alloy steels was evaluated from a view point of the temperature dependency with phase fraction of tempered martensite controlled by cooling rate. Additionally, a possible modification of the fracture toughness master curve was proposed and discussed.

2. Previous works

Fig. 1 shows the standard master curves together with the K_{Jc} values of tempered martensitic SA508 Gr.4N low alloy steel (KL4-Ref) and commercial bainitic SA508 Gr.3 low alloy steel (H3). As can be seen, the data distribution of H3 was well fit to the master curve shape through the whole temperature range, even with the K_{Jc} values over the validity limit at a high temperature. However, figure 1(a) shows that, at the low test temperatures, all values are located below the median curve. On the contrary, the data set at high temperature of -140°C was deviated from the upper region of the median curve. Therefore, it was considered that the dependency of the K_{Jc} values on the temperature in KL4-Ref was steeper than that predicted by the standard master curve.

In order to assess the influence of the data distribution on the T_0 determination, the T_0 obtained from all data was compared with the T_0 values calculated from each single temperature data sets. According to the results of H3, the T_0 values from each data set deviated only 7°C from the T_0 that was determined from all data sets. However, in the case of KL4-Ref, the differences among the T_0 values from individual data sets were extensively large and the T_0 values determined by the single temperature analysis decreased with a rise in test temperature. These results may have arisen from the steeper dependence of the K_{Jc} values on the temperature, which was mentioned in the previous paragraph.

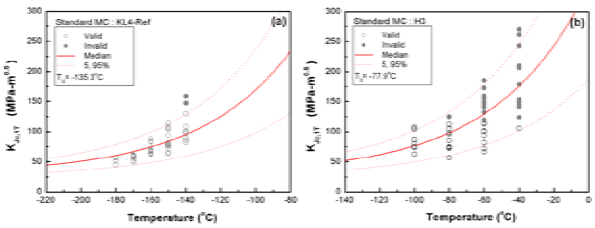

Fig. 1. Standard master curves and measured K_{Jc} values of (a) tempered martensitic SA508 Gr.4N steel and (b) bainitic SA508 Gr.3 steel.

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 quenching, in 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.

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

Fracture toughness tests were carried out in 3-point bending with 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.

4. Results and Discussion

Fig. 2 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 in iced water (cooling rate: 16^{o}C/s) should have almost a fully martensitic microstructure. On the other hand, the specimen cooled in air (0.5^{o}C/s) is expected to have some portion of bainite within its microstructure since the cooling curve passed through the region of bainite formation.

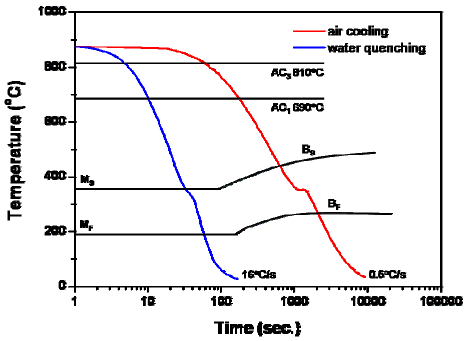

Fig. 2. Cooling curve profiles for the different cooling rates plotted with the CCT diagram of SA508 Gr.4N steels.

Optical micrographs of the specimens confirm the microstructure as shown in Fig. 3. The micrographs of both steels showed the microstructure consisted of prior austenite grain boundaries and the packets of parallel lath. However, the KL4-Ref quenched at 16^{o}C/s appeared a more complex microstructure. The microstructure of the specimen cooled at 0.5^{o}C/s appeared in the mixed-structure of predominantly tempered martensite and bainite, in which the volume fraction of martensite was about 67% in the former research [10]. On the other hand, the microstructures of KL4-Ref quenched at 16^{o}C/s consisted of almost fully tempered martensite as expected.

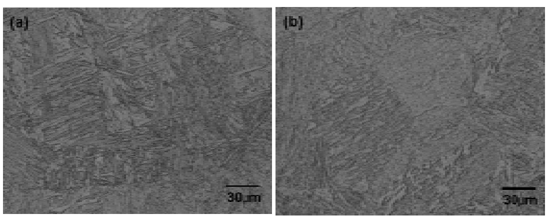

Fig. 3. Optical micrographs of KL4-Ref (a) quenched at 16^{o}C/s and (b) cooled at 0.5^{o}C/s.

Fig. 4 shows the standard master curves together with the K_{Jc} values of KL4-Ref quenched at 16^{o}C/s. Although the number of data points was small compared to that of KL4-Ref cooled at 0.5^{o}C/s, it generally indicated a steeper dependency of K_{Jc} values with temperature than that predicted in the standard master curve. The additional evaluation of the transition behavior in SA508 Gr.4N low alloy steels with different phase fraction of tempered martensite is presently undergoing analysis on the effect of microstructural change on the transition behavior.

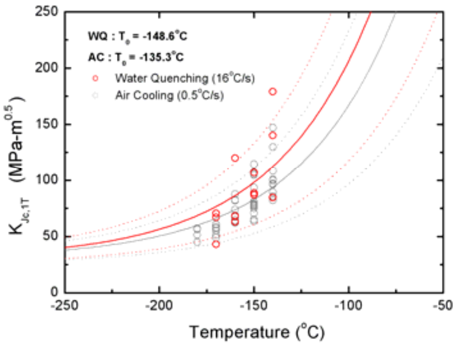

Fig. 4. Standard master curves together with the K_{Jc} values of KL4-Ref quenched at 16^{o}C/s

5. Summary

This work focused on the evaluation of fracture toughness in tempered martensitic SA508 Gr.4N low alloy steels from a view point of the effect of phase fraction of tempered martensite on the transition behavior. As predicted from the cooling curves plotted in TTT diagram, the microstructures of the specimens cooled at 0.5^{o}C/s consisted of the tempered martensite of about 67% volume fraction and tempered bainite, while the KL4-Ref quenched at 16^{o}C/s appeared as almost fully tempered martensite. In the results of fracture toughness tests, the K_{Jc} evolution with a temperature of KL4-Ref quenched at 16^{o}C/s showed a steeper transition than that of KL4-Ref cooled at 0.5^{o}C/s as well as that of bainitic commercial RPV steel. The additional evaluation of the transition behavior in SA508 Gr.4N low alloy steels with different phase fraction of tempered martensite is presently undergoing research on the relationship between microstructural change and transition behavior.

Acknowledgement

This work is carried out under the Nuclear R&D program by the Ministry of Knowledge Economy.

REFERENCES

[1] Y. R. Im et al, J. Nucl. Mater. 297 (2001) 138-148
[2] K. Suzuki, J. Nucl. Mater. 108&109 (1982) 443-450
[3] J. R. Hawthorne et al, Nucl. Eng. Des. 18 (1988) 221
[4] ASTM E1921-09c, ASTM International, 2009
[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
[9] B. L. Bramfitt et al, Proceedings of the 31st mechanical working and steel processing, ISS of AIME, 1990, 443
[10] S. G. Park et al, Proceedings of the 12th international conference on pressure vessel technology, 2009, 124