Transactions of the Korean Nuclear Society Spring Meeting
Gwangju, Korea, May 30-31, 2013

Effect of Cooling Rate on Microstructures and Mechanical Properties in SA508 Gr4N High Strength Low Alloy Steel

Min-Chul Kim, Sang-Gyu Park, Kwon-Jae Choi, Bong-Sang Lee
KAERI, Nuclear Material Research Div.,Daedeok-daero 989-111, Yuseong-gu, Daejeon, 305-353, Korea
**Corresponding author: mckim@kaeri.re.kr*

1. Introduction

In the ASME SA508 material specifications of quench-and-tempered RPV steels, SA508 Gr.4N Ni-Cr-Mo low alloy steel has improved strength and impact toughness compared to commercial SA508 Gr.3 Mn-Mo-Ni low alloy steel. The improved mechanical properties come from its microstructural changes caused by enhanced hardenability owing to increased Ni and Cr contents. The microstructure of Ni-Cr-Mo low alloy steel is a mixture of tempered martensite and tempered lower bainite and that of Mn-Mo-Ni low alloy steel is predominantly tempered upper bainite. Higher strength and toughness steels are very attractive as an eligible RPV steel, so several researchers have studied to use the Ni-Cr-Mo low alloy steel for the NPP application [1,2].

Because of the thickness of reactor vessel, there are large differences in austenitizing cooling rates between the surface and the center locations of thickness in RPV [3]. Because the cooling rates after austenitization determine the microstructure, it would affect the mechanical properties in Ni-Cr-Mo low alloy steel, and it may lead to inhomogeneous characteristics when the commercial scale of RPV is fabricated. In order to apply the Ni-Cr-Mo low alloy steel to RPV, it is necessary to evaluate the changes of microstructure and mechanical properties with varying phase fractions in Ni-Cr-Mo low alloy steel.

In this study, the effects of martensite and bainite fractions on mechanical properties in Ni-Cr-Mo low alloy steel were examined by controlling the cooling rate after austenitization. First of all, continuous cooling transformation(CCT) diagram was established from the dilatometric analysise. Then, the phase fractions at each cooling rate were quantitatively evaluated. Finally, the mechanical properties were correlated with the phase fraction, especially fraction of martensite in Ni-Cr-Mo low alloy steel.

2. Experimental Procedure

The model alloy of KL4 with a typical composition of the SA508 Gr.4N steel was selected within ASME specified composition. The chemical composition of the steel is given in Table 1. The model alloy was austenitized at 880°C for 2 hours followed by different cooling rates (16°C/sec, 0.47°C/sec, 0.11°C/sec and 0.05 °C/sec), and then tempered at 660 °C for 10 hours..

Table 1. Chemical compositions of the model alloy (wt%)

C	Mn	Ni	Cr	Mo	Fe
0.19	0.30	3.59	1.79	0.49	bal.

The dilatation curves of the different cooling rates were measured by the Dilatronic III dilatometer of Theta industries. The specimens were heated to 880°C and held for 3 minutes in a vacuum, then cooled to room temperature at seven different cooling rates from 16 to 0.03°C/sec. Microstructure observations were made using an optical microscope and a scanning electron microscope (SEM). The crystallographic orientations of microstructures were observed by Electron Back-Scatter Diffraction (EBSD) using a JSM-700F field-emission SEM.

The tensile properties of the alloys were evaluated using a MTS universal static testing machine at a stain rate of 9.3×10^{-4}/sec at room temperature. Impact energy transition curves were obtained using standard Charpy V-notched specimens in accordance with ASTM E23. Impact tests were conducted using the SATEC-S1 impact test machine with a maximum capacity of 406J in a temperature range of -196 °C to 100°C.

3. Results and Discussion

From the changes of slope in dilatometer curves, the start and end temperature of phase transformation can be determined. The start temperature of phase transformation is decreased with an increase of cooling rate due to the delay of diffusion controlled bainite transformation in rapid cooling conditions [4]. The continuous cooling transformation (CCT) diagram is constructed from the dilatometer curves, which shows overall trend of bainite and martensite transformation as shown in Fig. 1. It shows very similar result to the CCT diagram of HY-80 steel (3.3Ni-1.8Cr-0.5Mo low alloy steel) reported by Bramfitt [5]. It was clearly observed in Fig. 1 that the fully martensitic transformation occurred at the cooling rate of 16°C/sec, and the fully bainitic transformation occurred at the cooling rate of lower than 0.12°C/sec. Martensite start(Ms) temperature determined from the dilatometer curve at the cooling rate of 16°C/sec was around 372°C. In the low alloy steels, the Ms temperature is generally depends on the chemical compositions of the steels, thus it can be calculated by the empirical equation suggested by Andrew [6]. In this study, the Ms temperature calculated by Andrew's equation is 361°C which is almost identical with the value obtained from the dilatometer curve at cooling rate of 16°C/sec.

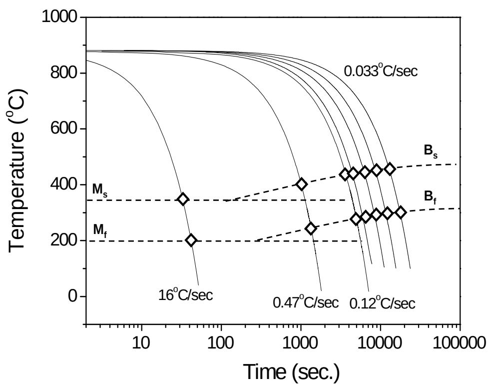

Fig. 1. CCT curve of the Ni-Cr-Mo low alloy steel based on dilatometer curve

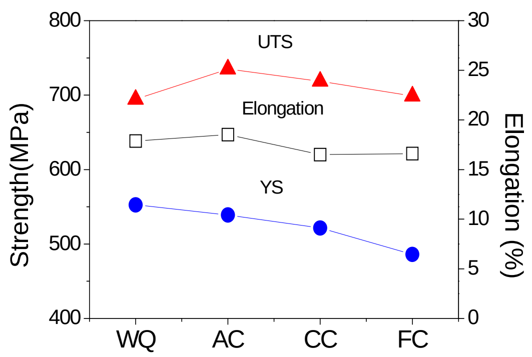

Fig. 2. Tensile properties of the model alloys with different cooling rates

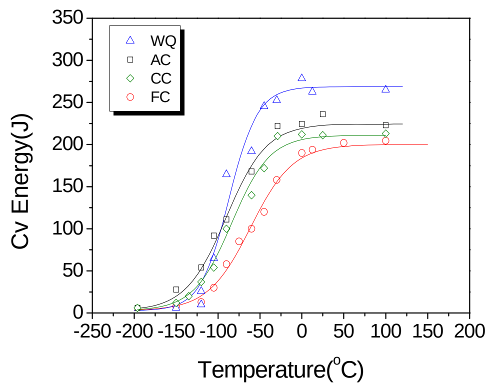

Fig. 3. Charpy impact test results of the model alloys with different cooling rates

Fig. 2 shows the tensile test results of the specimens. The yield strength of alloy is linearly increased with an increase of cooling rates. The yield strength of WQ showed the highest value of 552MPa, and those of AC, CC, and FC were 540MPa, 521MPa, and 486MPa, respectively. The elongations were similar in all specimens ranged from 17 to 19%. Fig. 3 shows the Charpy impact transition curves of the WQ, AC and FC. FC showed the poor transition properties, and its Ductile-Brittle Transition Temperature (DBTT) was as high as -62 °C, while WQ, AC, and CC were -90°C, -88 °C, and -81°C, respectively. The Upper shelf energy (USE) value was increased with an increase of cooling rates. The USE of WQ, AC, CC, and FC were 268J, 224J, 213J, and 200J, respectively.

3. Summary

The effects of phase fractions on microstructure and mechanical properties in Ni-Cr-Mo low alloy steel were evaluated. The changes in phase fractions of Ni-Cr-Mo low alloy steel with different cooling rates were analyzed by the dilatometer, and then the phase fractions were compared with its microstructural observation and mechanical test results. From the dilatometer curves, a drastic change of martensite fractions is observed between the cooling rates of 0.07 °C/sec and 0.12°C/sec. The yield strength is linearly increased with martensite fraction. Ductile-brittle transition temperature is decreased with an increase of martensite fraction, but the transition behaviors are similar over 65% martensite due to the similarity of precipitation behavior..

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] Y. R. Im, Y. J. Oh, B. J. Lee, J. H. Hong, H. C. Lee, J. Nucl. Mater., Vol.297, p.138, 2001

[2] Y. S. Lee, M. C. Kim, B. S. Lee, C. H. Lee, J. Kor. Inst. Met. Mater., Vol.47, p.139, 2009

[3] J. T. Kim. H. K. Kwon, Y. B. Il, H. S. Jang, J. Kor. Soc. of Mech. Eng. Vol.37, p.43, 1997

[4] T. A. Kop, P. G. Remijn, V. Svetchnikov, J. Sietsma, S. V. Zwaag, J. Mat. Sci., Vol.**36,** p.1863, 2001

[5] B. L. Bramfitt, J. G. Speer, 31st Mechanical Working and Steel Processing, Proceedings

[6] K. W. Andrews J. Iron and Steel Inst., Vol.203, p.721, 1965