Transactions of the Korean Nuclear Society Autumn Meeting
PyeongChang, Korea, October 30-31, 2008

Effects of the P and Mn on Temper Embrittlement in SA508 Gr. 4N Low Alloy Steel

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1. Introduction

It is well known that SA508 Gr.4N low alloy steel has improved fracture toughness and strength, compared to commercial low alloy steels such as SA508 Gr.3 and SA533B which have less than 1% Ni. higher strength and fracture toughness of low alloy steels could be achieved by increasing the Ni and Cr contents. So there are several researches in SA508 Gr.4N low alloy steel for a RPV application[1]. By the way, the operation temperature of reactor pressure vessel is more than 300℃ and operating over 40 years. Therefore, in order to apply the SA508 Gr.4N low alloy steel for a reactor pressure vessel, it requires phase stability in the high temperature range. Especially, we need to evaluate the temper embrittlement phenomena of SA508 Gr.4N for a RPV application.

In this study, we have performed a Charpy impact test and tensile test of SA508 Gr.4N low alloy steel with changing impurity element contents such as Mn and P. And also, the mechanical properties of these low alloy steels after long-term heat treatment(450℃, 2000hr) are evaluated. And then, the images of the fracture surfaces are observed and grain boundary segregation is analyzed by AES. Based on the experimental results, we discussed the temper embrittlement effect including thermodynamic calculation.

2. Experimental Procedure

Three types of pressure vessel steels with different impurity contents were selected for this study. The chemical compositions of the steels are given in Table 1. A model alloy KL4-Ref with a typical composition of the SA508 Gr. 4N steel was arranged as a reference alloy within ASME specified composition. It was planned to enforce the temper embrittlement effect in the SA508 Gr. 4N low alloys steel by increasing P content(KL4-P). The model alloy SC-KL4 was intended to restrict the temper embrittlement effect by limiting impurity contents. However, since the difficulty in the P content control, there are no difference of the P contents in the KL4-Ref and SC-KL4. The main difference between KL4-Ref and SC-KL4 is its Mn content. Model alloys were austenitized at 880℃ for 2 hours followed by an air cooling, and then tempered at 660℃ for 10 hours. After the tempering process, model alloys were treated at 450℃ for 2000 hours, which can reveal the temper embrittlement phenomena efficiently[2].

Tensile properties of a alloys were evaluated using MTS universal static testing machine. Yield strength was determined by 0.2% strain offset stress, or by lower yield stress. Impact transition curves were obtained using standard Charpy V-notched specimens and using SATEC-S1 impact test machine with maximum capacity of 406J in a temperature range of -196℃ to 100℃. The index temperatures were determined from fitted Charpy curves as the temperature corresponding to the Charpy energy value of 48J and 68J.

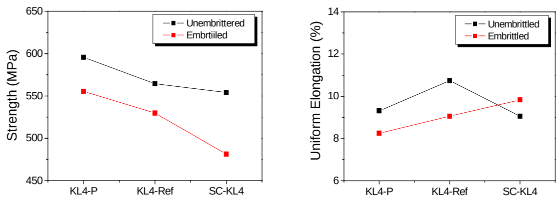
The observations of the fractures were conducted using scanning electron microscope (SEM). The specimens were examined using SEM-6300 scanning electron microscope. Auger electron spectroscopy was used to monitor grain boundary segregation in the model alloy. All samples were fractured at low temperature (lower than -150℃) in $2x10^{-10}$ torr, and the fracture surfaces were analyzed at 5kV. A ULVAC PHI 700 auger electron microscope was employed for the analysis. Thermodynamic calculation is performed using DICTRA. The database is TEFE 5. and MOB2.

Table 1. Chemical compositions of steels. (wt%)

	C	Mn	Ni	Cr	P	Fe
KL4-Ref	.190	.297	3.59	1.79	.002	Bal.
KL4-P	.209	.328	3.63	1.87	.029	Bal.
SC-KL4	.200	.007	3.50	1.80	.002	Bal.

3. Experimental Results and Discussion

Fig. 1 shows the tensile test results of the model alloys. The yield strength of the all model alloys were decreased after the long-term heat treatment, due to the softening of the steels. However, the uniform elongation of the steels show different behavior compared to the yield strength. In the case of the SC-KL4, the uniform elongation was increased after long-



(a) (b)

Fig. 1 Tensile test results of the model alloys.
(a) Yield strength (b) Uniform elongation.

term heat treatment by the softening of the matrix. On the contrary, the uniform elongation of the KL4-Ref and KL4-P were decreased after the long-term heat treatment which means the embrittlement of the steels.

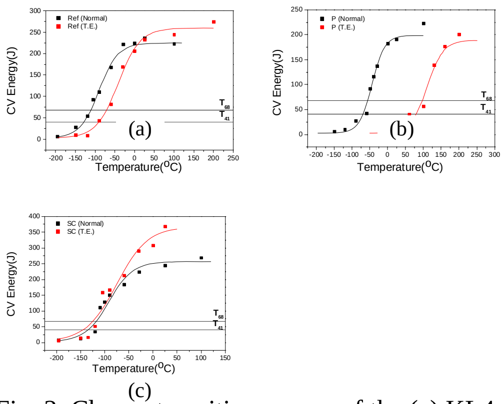


Fig. 2 Charpy transition curves of the (a) KL4-Ref, (b) KL4-P and (c) SC-KL4

Similar tendency is observed in the Charpy impact test. Fig. 2 shows the Charpy impact test results. It is seen that the transition curve of the KL4-P and KL4-Ref is shifted to the higher temperature region, while the transition region was not changed in the SC-KL4.

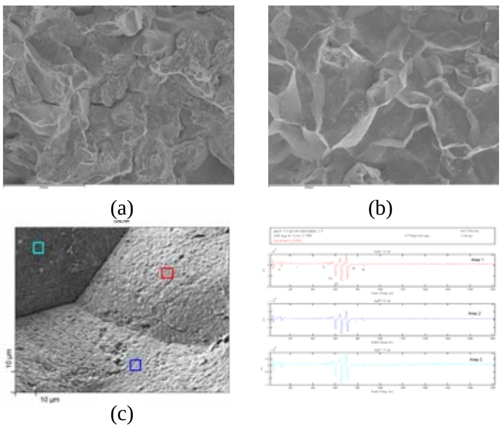


Fig. 3 Fracture analysis of KL4-P
(a)SEM (normal), (b)SEM (embrittled), (c) AES

In order to analyze the fracture behavior, the fracture surfaces of the model alloys are observed by SEM and AES. Fig. 3 shows the fracture surface of the KL4-P in the lower transition region and its AES analysis result. In the SEM observation results, the fracture behavior of the KL4-P is changed from the partial intergranular to the almost intergranular after the long-term heat treatment. AES analysis result is shown in Fig. 3(c). From the AES result, the grain boundary segregation of the several elements was observed. And also, the segregation elements are not only the impurity element P but also the alloying element Ni. Based on the mechanical test and fracture surface analysis results, it is concluded that KL4-P is embrittled after the long-term heat treatment, and it is caused by grain boundary segregation such as P and Ni. It can be also deduced that KL4-Ref is embrittled by similar phenomena.

However, KL4-Ref and SC-KL4 show the different embrittlement behavior after the long-term heat treatment in spite of the same P and Ni contents. The main difference of these two model alloys are Mn content. In order to investigate the Mn effect, we calculated the diffiusivity of the P and Ni with changing Mn contents using DICTRA. In the calculation result, the diffusivity of the P is not changed with increasing Mn contents. On the other hand, the diffusivity of the Ni is increased with increasing Mn contents. It is reported that the Ni and P have a strong interaction[4]. So the Mn affects the grain boundary segregation of Ni and it also causes the segregation of P, which occurs the temper embrittlement.

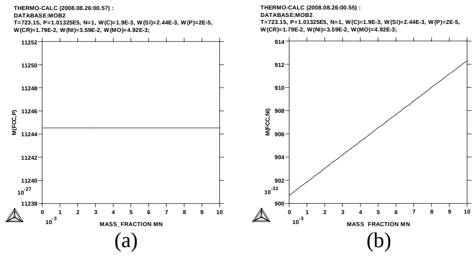


Fig. 4 Calculation results of the mobility with Mn contents (a) P (b) Ni

4. Summary

In this study, evaluation of the temper embrittlement on SA508 Gr.4N low alloy steel by mechanical test and fracture analysis. Temper embrittlement is occurred in KL4-Ref and KL4-P, which show the decrease of the elongation and the shifting of the transition curve. The reason of the temper embrittlement is grain boundary segregation of the impurity element P and alloying element Ni. However, KL4-Ref reveals the temper embrittlement phenomena despite the same contents of P and Ni compared with SC-KL4. This result is may caused by the Mn contents.

Acknowledgement

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

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