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Evaluation of the Temper embrittlement in SA508 Gr. 4N Low Alloy Steel with Ni, Cr Contents Variation

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1. Introduction

It is well known that SA508 Gr.4N low alloy steel has an 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 Ni and Cr addition. So there are several researches on SA508 Gr.4N low alloy steel for a RPV application[1]. The operation temperature of a reactor pressure vessel is more than 300℃ and it operates for 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 including temper embrittlement resistance. Although temper brittlement has not been reported in SA508 Gr.4N low alloy steel, the evaluation of the temper embrittlement phenomena on SA508 Gr.4N is required for an RPV application. In a previous study, we have concluded that additional Ni and Cr could change the microstructures of SA508 Gr.4N low alloy steel[2], and changeed microstructure may affect the susceptibility of temper embrittlement in SA508 Gr.4N.

In this study, we have performed a Charpy impact test of SA508 Gr.4N low alloy steel with changing alloying element contents such as Ni and Cr. The mechanical properties of these low alloy steels after a long-term heat treatment(450℃, 2000hr) are also evaluated. Then, the fracture modes of each impact specimens are examined and grain boundary segregation is analyzed by AES. The precipitation behaviors of the low alloy steels are observed by SEM.

2. Experimental Procedure

Five types of model alloys with different Ni and Cr 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 study the temper embrittlement effect in the SA508 Gr. 4N low alloys steel by changing Ni (KL4-Ni1, KL4-Ni2) and Cr (KL4-Cr1, KL4-Cr2) contents. 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[3].

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 150℃. The index temperatures were determined from fitted Charpy curves as the temperature corresponding to the Charpy energy values of 41J 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.

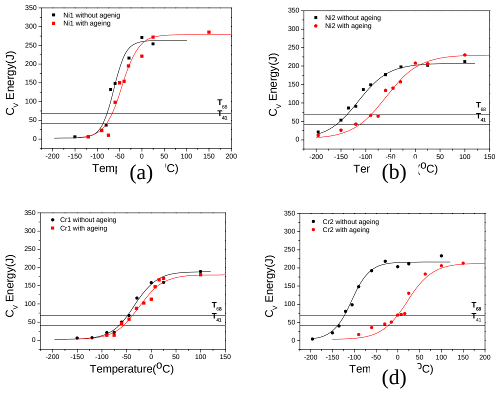
Table 1. Chemical compositions of steels. (wt%)

	C	Mn	Ni	Cr	P	Fe
KL4-Ref	.190	.297	3.59	1.79	.002	Bal.
KL4-Ni1	.215	.334	2.66	1.81	.002	Bal.
KL4-Ni1	.208	.319	4.82	1.83	.002	Bal.
KL4-Cr1	.212	.326	3.63	1.04	.002	Bal.
KL4-Cr2	.211	.323	3.64	2.47	.002	Bal.

3. Experimental Results and Discussion

Fig. 1 shows the Charpy impact test results. From the transition curve, it is apparent that both of the higher Ni and Cr steels KL4-Ni2, KL4-Cr2 experienced a greater upward shift in the index transition temperature(T_{41J}) after long term heat treatment. It gives the initial T_{41J} of -160.2℃ in KL4-Ni2 and -139.2℃ in KL4-Cr2, compared with -112.8℃ and -22.7℃ after ageing, respectively. On the other hand, the index transition temperature was slightly increased in the KL4-Ni1 and KL4-Cr1. The index transition temperature(T_{41J}) of KL4-Ni1 and KL4-Cr1 were elevated about 10℃ after ageing.

In order to analyze the fracture behavior, the fracture surfaces of the model alloys are observed by SEM. Fig. 2 shows the fracture surface of the model alloys in the lower transition region. In the SEM observation results, the fracture behavior of the KL4-Ni2 and KL4-Cr2 show almost intergranular manner after a long-term heat treatment. However, the fracture appearance of the KL4-Ni1 and KL4-Cr1 does not show any intergranular behavior in the same condition. Based on the



(c)

Fig. 1 Charpy transition curves of the (a) KL4-Ni1, (b) KL4-Ni2, (c) KL4-Cr1 and (d) KL4-Cr2

mechanical test and fracture mode observation results, KL4-Ni2 and KL4-Cr2 are severely embrittled after the long-term heat treatment while KL4-Ni1 and KL4-Cr1 show little embrittlement behavior in spite of same P contents. Therefore, it is considered that the susceptibility to temper embrittlement in SA508 Gr.4N low alloy steel is enhanced with increasing Ni and Cr contents.

In the previous research, it is concluded that Ni does not affect the temper embrittlement directly, though it is co-segregated with P in the grain boundary. However,

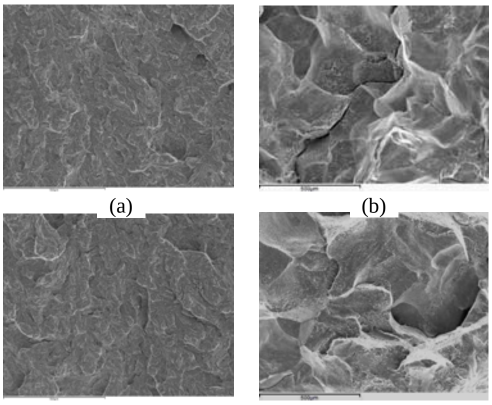


Fig. 2 Fracture analysis of model alloys
Before ageing (a)KL4-Ni1 (b)KL4-Ni2,
After ageing (c) KL4-Cr1, (d) KL4-Cr2

the susceptibility of temper embrittlement is higher in martensite structure than that of the bainite structure[4], and the volume fraction of matrensite is significantly increased with an increase of Ni contents. Therefore, we can suppose that the Ni indirectly lowers the temper embrittlement resistance by changing microstructure. Unlike the Ni, Cr does not affect the change of volume fraction of martensite largely, and it does not segregated in the grain boundary. It has been reported that an additional Cr in the matrix which does not consumed by carbide precipitation, could enhance the P segregation[5]. In order to investigate the Cr effect in the model alloys, we calculated the composition of the matrix(ferrite) at 450℃ with changing Cr contents using Thermocalc(Fig.3). In the calculation result, the fraction of the Cr in the matrix is sharply increased over 1.7 wt% Cr, which is similar in Cr content of KL4-Ref, with increasing Cr content. So the additional Cr in KL4-Cr2 accelerates the grain boundary segregation of P, which enhances the temper embrittlement.

In addition to segregation enhancement of Cr,

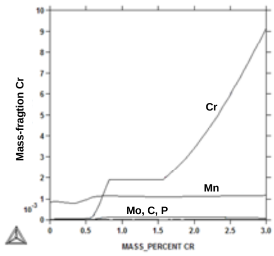


Fig. 3 Calculation results of the mobility of P with Mn contents

decreased C content in the matrix may lower the temper embrittlement resistance. It is reported that C segregated itself in the grain boundary and it reduces the segregation of P[6]. The fraction of C was decreased in KL4-Cr2 in the thermodynamic calculation. The segregation of C will be dicussed with AES in detail.

4. Summary

In this study, evaluation of the temper embrittlement on SA508 Gr.4N low alloy steel by a mechanical test and a fracture analysis was carried out. The severe temper embrittlement occurred in KL4-Ni2 and KL4-Cr2, which has higher Ni and Cr contents. It is estimated that the reason of the temper embrittlement by Ni addition is increased volume fraction of martensite. The differences in embrittlement behavior with different Cr model alloys are mainly caused by promotion of P segregation which affected by the additional Cr in the matrix.

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