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Effects of Intercritical Heat Treatment on Ductile-Brittle Transition Behavior of SA508 Gr.4N Model Alloys

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1. Introduction

The SA508 Gr.4N low alloy steel shows better properties with a higher strength and higher toughness than SA508 Gr.3 low alloy steel by a change in chemistry with increased Ni and Cr contents. For the application of SA508 Gr.4N low alloy steels to the pressure vessel in nuclear power plants, we have carried out comprehensive and systematic researches on SA508 Gr.4N in recent years [1-4]. Nuclear power plants operate for more than 40 years at temperature above 300°C. Therefore, in order to apply the SA508 Gr.4N low alloy steel for pressure boundary material, it requires a resistance of thermal embrittlement in the high temperature range including temper embrittlement resistance. It is reported that temper embrittlement phenomena occurred in rotor steels having similar chemical components to SA 508 Gr.4N low alloy steel when exposed to high temperatures for a long time. [5].

In this study, we have evaluated the effects of intercritical heat treatment on temper embrittlement behavior of SA508 Gr.4N low alloy steel. The changes of microstructure due to the application of the intercritical heat treatment were analyzed by optical microscope, scanning electron microscope and EBSD. In addition, the changes of tensile and Charpy impact properties were also evaluated. By comparing the brittle-ductile transition behaviors of samples before and after aging, the effects of intercritical heat treatment on resistance to temper embrittlement of SA508 Gr.4N model alloy is characterized.

2. Experimental Procedure

The chemical compositions of the model alloy used in this study are given in Table 1. A model alloy was prepared based on the composition of SA508 Gr.4N Ni-Cr-Mo low alloy steel, but the P contents were increased beyond the ASME specified composition range[6] in order to observe the P segregation behavior clearly. The model alloy was austenitized at 880 °C for 2 hours followed by air cooling and then tempered at 660 °C for 10 hours. Intercritical heat treatment was applied between austenitization and tempering process as described in fig. 1. The step cooling was adopted to accelerate embrittlement of model alloy. The step cooling is a heat treatment by cooling incrementally through the embrittling range: 5 hour 590 °C, 1 hour 575 °C, 15 hour 538 °C, 24 hour 524 °C, 48 hour 496 °C, 72 hour 468 °C, furnace cool. The sample that was not intercritically heat-treated was named PR, and the sample that was intercritical heat-treated was named PI.

The microstructures were investigated by an optical microscope and scanning electron microscope (SEM). The grain boundary structures were observed by Electron Back-Scattered Diffraction (EBSD) using a S-4800 field-emission scanning electron microscope. Tensile specimens were tested at room temperature and 288 °C. The yield strength was determined by a 0.2 % strain offset stress. Charpy impact tests were performed with standard Charpy V-notch specimens (10x10x55 mm) in the temperature range of −196 to 100 °C according to the ASTM E23 procedure. Hyperbolic tangent curve fitting was conducted for the absorbed impact energy data to obtain the characteristic temperatures.

Table 1. Chemical compositions of the model alloy used in this study (wt.%)

	C	Mn	Ni	Cr	Mo	Si	Cu	P	Fe
ASME Spec.	0.23 max	0.2-0.4	2.8-3.9	1.5-2.0	0.4-0.6	0.4 max	0.25 max	0.02 max	Bal.
PR	0.2	0.5	3.5	1.8	0.2	0.25	0.03	0.029	Bal.

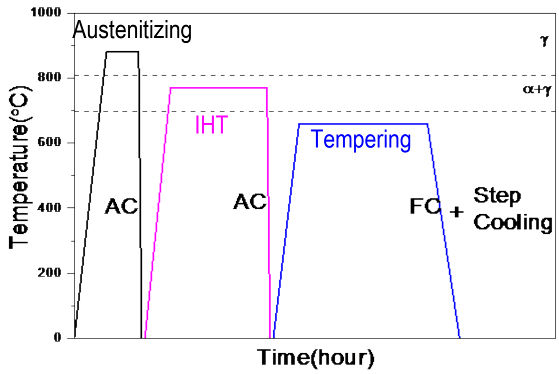

Fig. 1. Heat treatment process of the model alloys.

3. Results and Discussion

2.1 Microstructure

Fig. 2 shows the microstructural changes of the model alloys due to the application of intercritical heat treatment. The predominant microstructure of the SA508 Gr.4N model alloy is tempered martensite, though a mixture of martensite and bainite was observed in the optical micrographs. The size of the martensite packet including a lath structure is much smaller than that of the bainite packet or sheaf. The model alloy has finer precipitates than SA508 Gr.3 low alloy steels and most of the precipitates are known as Cr-rich carbides such as M_7C or $M_{23}C_6$ [7]. The grain size of the model alloy was reduced, but the precipitate was not changed by intercritical heat treatment.

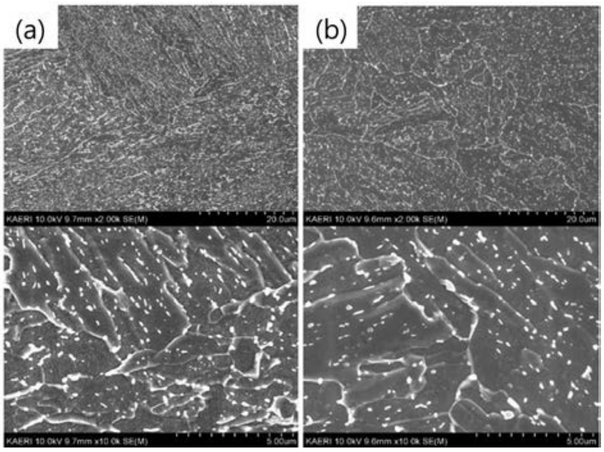

Fig. 2. Microstructure of the model alloys: (a) PR, and (b) PI

2.2 Mechanical Properties

By the application of intercritical heat treatment, the yield strength and tensile strength were decreased from 594(±6)MPa to 569(±6)MPa and from 783(±1)MPa to 764(±4)MPa, respectively. However, changes in Charpy transition properties of the model alloy with or without intercritical heat treatment was not noticeable. However, the amount of transition temperature shift(TTS) after aging treatment showed a large difference depending on whether intercritical heat treatment was performed or not. After aging treatment, the transition temperature of the PR increases by 161 degrees. However, when the intercritical heat treatment was performed, the transition temperature shift was remarkably reduced. And the fraction of intergranular fracture mode due to the impurity segregation boundaries tended to decrease.

Table 2. Summary of Charpy impact test results

	T_{41J} (°C)			USE(J)		
	Before Aging	After Aging	TTS	Before Aging	After Aging	TTS
PR	-87	74	161	200	204	4
PI	-85	28	113	213	226	13

4. Summary

The effects of intercritical heat treatment on temper embrittlement behavior of SA508 Gr.4N low alloy steel were evaluated. By the application of intercritical heat treatment, yield strength was decreased, but the transition behavior was not changed. However, transition temperature shift was decreased significantly. This means that the resistance to temper embrittlement is improved by the intercritical heat treatment.

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