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Compatibility Evaluation for Application of Lean Duplex Stainless Steels to Seawater Systems in Nuclear Power Plants

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Abstract. Lean duplex stainless steels have been developed in Korea for the purpose of being used in the seawater systems of industries. The flow velocity of some part of seawater systems in nuclear power plants is high and damages of components from corrosion are severe. Therefore, this environment requires using high strength and high corrosion resistant steels. The newly developed lean duplex stainless steels STS329LD(20.3Cr-2.2Ni-1.4Mo) and STS329J3L(22.4Cr-5.7Ni-3.6Mo) are evaluated for the compatibility in seawater systems of nuclear power plants. In this study, the physical & mechanical properties and corrosion resistance of two alloys were quantitatively evaluated in comparison with commercial stainless steel 316L. Microstructures and mechanical properties of them were analyzed and the electrochemical properties related to corrosion resistance were measured such as pitting potential, passive current density, and corrosion rates from Tafel analysis. Critical pitting temperatures were measured in accordance with ASTM G48E method. The pitting initiation time and lifetime for replacement were predicted from the PRE values of test alloys and empirical equations that have been formulated from the condenser tubes of a nuclear power plant.

Introduction

All of nuclear power plants in Korea are located in seashores and they are using seawater as cooling medium. Many nuclear power plants in Korea have applied carbon steels + rubber lining or Archcoat + cathodic protection to the pipes of circulating water systems including up to 84 inch diameter pipes [1]. Sometimes these large diameter seawater pipes have been experienced coating failures from blistering caused by coatings deterioration or over-protection current from cathodic protection systems. The localized corrosion such as pitting has inevitability followed these coating failures shown in Fig. 1.

Therefore, it may not a good option to select low corrosion resistant steels with polymeric coatings for the extended durability of components in seawater systems. It'll be desirable to apply solid materials that have high corrosion resistance and excellent mechanical properties in order to improve life extension and integrity, to decrease maintenance costs of components in seawater systems. Economic efficiency, of course, should be considered in advance.

Nowadays newly developed duplex stainless steels have been appeared that production costs decreased from reducing alloying elements of corrosion resistance while their mechanical properties and corrosion resistance were reserved compared to the traditional duplex stainless steels. These steels are called the lean duplex stainless steels that are expected to replace 316L stainless steel.

The reason that these lean duplex stainless steels are being concerned as materials for power plants is that they have enough price competitiveness even as a form of solid plate($t \leq 6$mm) not a lining form for seawater system pipes compared to expensive austenitic stainless steels.
In this study, theses newly developed lean duplex stainless steels in Korea are evaluated for their compatibility for seawater systems in nuclear power plants.

Fig. 1 Localized corrosion propagation after coating failures in seawater pipes

Experimental Procedures

Materials. Table 1 shows the composition of commercial STS 316L and those of newly developed lean duplex stainless steels, STS329LD and STS329J3L.

Table 1 Compositions of commercial STS316L and newly developed lean duplex stainless steels (unit: wt%)

	C	Si	Mn	P	S	Ni	Cr	Mo	Cu	Fe	PREN
STS316L	0.030	0.59	0.70	0.020	0.0010	12.2	17.5	2.2	0.01	Bal.	24.8
STS329LD	0.023	0.58	2.45	0.021	0.0004	2.2	20.3	1.4	0.02	Bal.	24.9
STS329J3L	0.025	0.55	1.46	0.026	0.0009	5.7	22.4	3.1	0.10	Bal.	32.5

*PREN = Cr + 3.3(Mo + 0.5W) + 30N

Mechanical tests. Surface hardness was measured by Rockwell hardness tester. Tensile test was performed at room temperature according to ASTM A370 [2]. Cross head speed was 1mm/min.

Corrosion tests; Anodic polarization tests were performed in 30°C 0.1% NaCl, 1.0% NaCl, and 3.5% NaCl solutions using a Potentiostat (Gamry DC105). All specimens were ground to SiC paper - #600 grit. The solutions were deaerated by purging with prepurified nitrogen gas (90 ml/min) for 30 minutes before specimen immersion. After immersion, the sample was cathodically polarized for 10 minutes at -700mV (SCE). Specimens were potentiostatically held for 10 minutes at open circuit potential and subsequently polarized anodically from the corrosion potential at a scan rate of 1 mV/sec. A saturated calomel electrode (SCE) was used as the reference electorde and high-density graphite rods were used as counter electrodes. Also, Tafel tests were performed in the above corrosion condition. The critical pitting temperature (CPT) was determined according to ASTM G48, by immersing in of 6%$FeCl_3$ + 1%HCl [3]. The experimental alloys were cut into 2 x 2 cm and ground to SiC paper - #600 grit.

Results and Discussion

STS329LD and STS329J3L show duplex structure – austenite and ferrite and the contents of ferrite were 51% and 59% respectively. Fig. 2 shows the $\Delta PREN_{30}$ of STS329LD and STS329J3L. $\Delta PREN_{30}$ defines the value of subtracting $PREN_{30}\alpha$ from $PREN_{30}\gamma$ meaning difference of corrosion resistance between phases. $\Delta PREN_{30}$ was calculated by 'Alloy design program'[4] and when its value shows zero, corrosion resistance will increase. Two steels showed small values and a similar $\Delta PREN_{30}$. It means that alloying design was appropriated.

Mechanical properties were evaluated by hardness and tensile tests. The Rockwell hardness values of developed lean duplex steels are 18.3HRC (STS329LD) and 22.6HRC (STS329J3L). The tensile strengths of them are 718MPa (STS329LD) and 788MPa (STS329J3L) respectively. In addition, the yield strengths of them are 563MPa (STS329LD) and 649MPa (STS329J3L). STS329J3L has more alloying elements and ferrite phase. Therefore, the most likely explanation is that the higher mechanical properties of STS329J3L are attributed to solid solution hardening effect and 10% higher ferrite phase ratio of it.

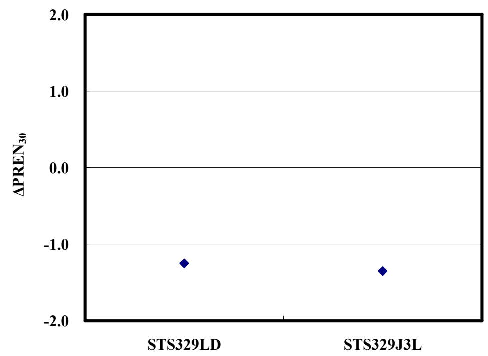

Fig. 2 $\Delta PREN_{30}$ of newly developed lean duplex stainless steels

From the APT(Anodic Polarization Test) curves, the pitting potentials of STS329J3L varying with NaCl concentration(30°C, 0.1%, 1.0%, 3.5% NaCl) are higher than those of STS329LD reaching to oxygen generation potential as shown in Table 2.

Table 2 Pitting potentials of test alloys from APT curves

	0.1% NaCl	1.0% NaCl	3.5% NaCl	PREN
316L	683mV(SCE)	500mV(SCE)	383mV(SCE)	24.8
329LD	Eo_2 ≒	787mV(SCE)	584mV(SCE)	24.9
329J3L	Eo_2 ↑	Eo_2 ↑	Eo_2 ↑	32.5

Tafel line analysis reveals that the mean corrosion rates of STS329J3L with variation of NaCl concentration are lower than those of STS329LD (Fig. 3).

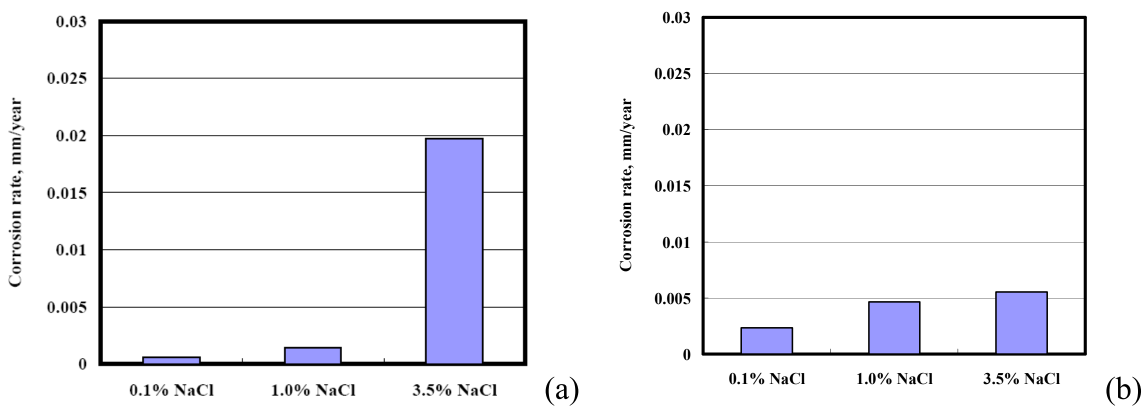

Fig. 3 Corrosion rates of test alloys calculated from Tafel line in NaCl solutions (a) STS329LD, (b) STS329J3L

The CPT of STS329LD is 25°C and that of STS329J3L is 45°C from the experiment conforming to ASTM G48 method E with solution of 6%$FeCl_3$ + 1%HCl. Fig. 4 displays the CPT data of two test alloys with the scale of $PREN_{30}$. As shown in Fig. 4, corrosion resistance of STS329LD was better than STS 316L stainless steel even with same PREN values. This is due to the galvanic coupling effect of austenite and ferrite phases and very low $\Delta PREN_{30}$. High corrosion resistance of STS 329LD is resulted from relatively high Cr and Mo contents. On the base of the reports for Cr and Mo additions [7, 8], by the Cr and Mo alloying, the incorporation of MoO_4^{2-} and CrO_4^{2-} in the passive film modified the immediate surrounding lattice and the resulting bipolar film rectified ionic current so as to resist ingressing progression of anions such as Cl^- and OH^-, and to enhance the egress of protons. As an indirect result of bipolarity, an interfacial glassy oxide of $xCr_2O_3 \cdot yCrO_3$ was developed which acted as a barrier layer. Also, there are many reports that oxyanions such as CrO_4^{2-} , MoO_4^{2-} , WO_4^{2-} , and nitro-oxyanions are very important factors in corrosion resistance of stainless steels [9-11].

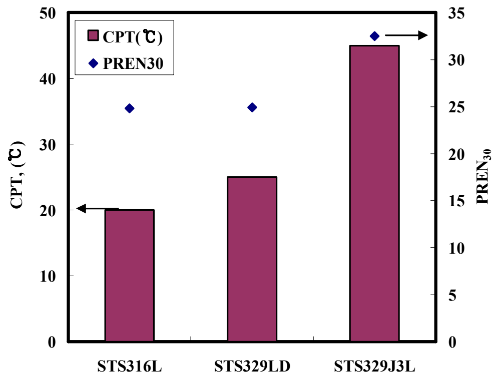

Fig. 4 CPT data of test alloys with overlapped scale of $PREN_{30}$

The below equations for life prediction were applied to the two test alloys that were used for life prediction of condensers of a nuclear power plant [5, 6]. These equations may be used for the equipments exposed to seawater. The pitting initiation time of STS329LD is 3.6 years and the lifetime for replacement of it is 7.3 years from Eq. 1 & 2 respectively. On the other hand, the pitting initiation time of STS329J3L is 12.4 years and the lifetime for replacement of it is calculated as 24.8 years.

$$\text{Pitting initiation time, year} = 0.068 \cdot \exp(0.16 \cdot PREN) \quad (1)$$

$$\text{Lifetime for replacement, year} = 0.136 \cdot \exp(0.15 \cdot PREN) \quad (2)$$

Summary

Excellent mechanical properties and corrosion resistance of duplex stainless steel matrix have attracted many researchers to alleviate its shortcomings. Lean duplex stainless steels have enough price competitiveness compared to expensive austenitic stainless steels because they have less expensive alloying elements. From the data of mechanical properties and corrosion resistance, some lean duplex stainless steels have superior mechanical properties and corrosion resistance comparing to austenitic stainless steels such as widely available 304L and 316L. Lean duplex stainless steel, in the mean time, has better welding properties and production recovery rates than traditional duplex stainless steels due to less precipitation of vulnerable phases such as σ phase. One of developed lean duplex stainless steels is expected to be a promising material for seawater systems in nuclear power plants.

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