

Mechanical and electrochemical characteristics in sea water of 5052-O aluminum alloy for ship

Seong-Jong KIM, Seok-Ki JANG, Min-Su HAN, Jae-Cheul PARK, Jae-Yong JEONG, Sang-Ok CHONG

Division of Marine Engineering, Mokpo Maritime University, Haeyangdaehak-ro 91 Mokpo-Si, 530-729, Korea

Received 21 May 2012; accepted 27 September 2012

Abstract: The optimum corrosion protection potentials were examined for 5052-O Al alloy, which is mainly used in ships. Various electrochemical experiments were carried out and the surface morphologies of specimens were observed by scanning electron microscopy (SEM) in order to determine the optimum corrosion protection potential to overcome pitting, corrosion, stress corrosion cracking (SCC), and hydrogen embrittlement in sea water. An optimum protection potential range of -1.3 V to -0.7 V was determined under the application of an impressed current cathodic protection (ICCP) system. The low current densities were shown in the range of -1.3 V to -0.7 V in the electrochemical experiments and good specimen surface morphologies were observed after potentiostatic experiment.

Key words: aluminum alloy; corrosion; electrochemical characteristics; stress corrosion cracking; hydrogen embrittlement; sea water corrosion; cathodic protection

1 Introduction

Recently, Al alloys are in the spotlight in many industrial areas as an environment-friendly material reducing the environment pollution. Al alloys have such characteristics of higher corrosion resistance and lower melting points compared to other metals [1]. Also, they are easily recyclable and enable to reduce the weight of production constructed by Al alloys because of light metals among the nonferrous metals [2]. Furthermore, they have excellent mechanical characteristics such as good machinability, weldability, high fatigue strength and good corrosion resistance in seawater environments [3,4]. Thus, the investigation of corrosion protection for Al alloys is very important to apply in marine environment which are exposed in seawater. Al alloys are used for the marine industries in various areas from government ships to warships and leisure vessels [5]. In order to extend the life spans of these vessels, it is important to find out the optimum corrosion resistance of Al alloys in application with heat treatment or adding various alloy elements. However, it is still revealed to corrosion in marine environment. Therefore, unceasing studies are under investigation to develop the corrosion technologies and various methods of corrosion protection

for Al alloy to extend vessels' life span and prevent marine accidents resulting from hull damage caused by superannuation in seawater environments.

In this study, the optimum corrosion protection potential was investigated through various electrochemical experiments subjecting to prevent marine accidents and marine pollution caused owing to corrosion and to contribute to the extension of vessels' life span by evaluating corrosion characteristics of the 5052-O Al–Mg alloys.

2 Experimental

5052-O Al alloy, which was composed of 2.91% Mg, 0.18% Si, 0.35% Fe, 0.19% Cr and balance Al, was used in this study. Tensile tests were performed with specimens manufactured to cross-section areas of 36 mm^2 with $R15$ radius of curvature and 50 mm gauge length. The electrochemical experiment specimens were mounted with epoxy resin to produce an exposed area of 1 cm^2 , polished with #2000 emery paper, and then carefully degreased with acetone and distilled water. The electrochemical experiments were conducted at a scan rate of 2 mV/s in seawater using Ag/AgCl (saturated KCl) reference electrode and a Pt coil counter electrode. This potential experiment was carried out for 86400 s, and

the anodic-cathodic polarization experiment was performed at -2.0 V to $+3.0$ V for an open circuit potential (OCP) after an initial delay time of 400 s. From the Tafel analysis of the resulting polarization curve, the corrosion potential and corrosion current density were determined from the OCP up to ± 0.25 V [6,7]. A potentiostatic experiment was then carried out at various potentials for 1200 s in order to detail the tendencies of the corrosion behavior. The resulting specimen surface morphologies were evaluated by a SEM.

3 Results and discussion

Figure 1 presents the stress—strain curves for rolling direction and vertical directions of the 5052-O Al alloy. The tests were carried out three times with the same methods as shown in Fig. 1. The results of the tensile tests conducted at two directions showed similar behaviors.

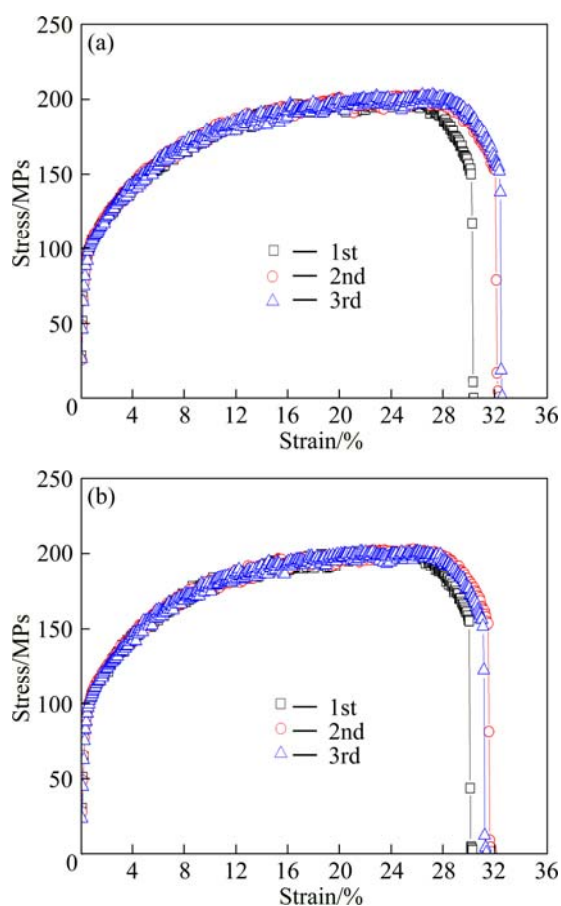


Fig. 1 Stress—strain curves of 5052-O Al alloy: (a) In rolling direction; (b) In vertical direction

Elastic deformation was shown at the beginning of tensile test, and rapidly increased to around 100 MPa. The maximum tensile strength was shown at the elongation of around 28%. The average mechanical properties measured through three experiments for the

rolling direction and vertical direction show the maximum tensile strength of 202.7 MPa and 202.0 MPa, yield strength of 95.21 MPa and 97.69 MPa, elongation of 29.86% and 30.92%, respectively.

Figure 2 shows the results of the natural potential of 5052-O Al alloy in seawater. At the beginning of immersion, the potential rapidly increased to -0.682 V in the noble direction due to the oxide films formed on the surface of the specimen, and when the experiment was finished, the potential was -0.681 V, thereby showing very stable behaviors in general. However, the potential showed somewhat unstable at around 75000 s. This is considered to be due to the repeated destructions and reformations of oxide films of the surface [8].

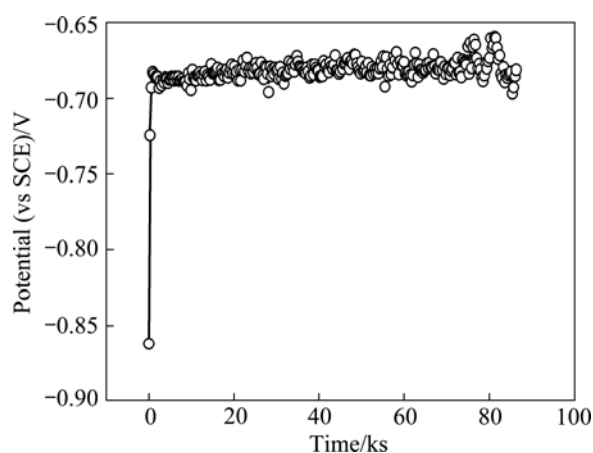


Fig. 2 Variation of potential for 5052-O Al alloy in seawater

Figure 3 shows the anodic polarization curves for 5052-O Al alloy in seawater. The experiment was conducted three times with the same method as shown in Fig. 3. The curves showed increasing of current density from -0.5 V due to active dissolution reactions and did not show the characteristics of passive states in general. Consequently, the passive state phenomenon in the 5052-O alloy, due to the formation of oxide films (Al_2O_3

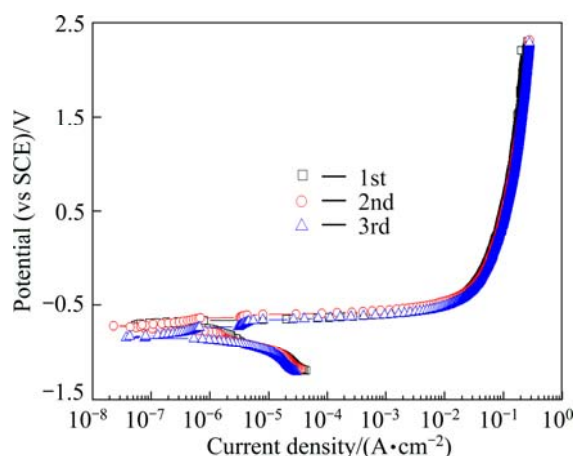


Fig. 3 Anodic polarization curves for 5052-O Al alloy in seawater

and $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$) on the surface, was not observed. The steady state of current density with the effect of active dissolution reactions was not found out. Therefore, the 5052-O Al alloy is considered to be vulnerable to stress corrosion cracking when the tensile stress works under corrosion atmospheres [9,10].

Figure 4 shows the cathodic polarization curve of 5052-O Al alloy in seawater. To review the overall tendency, as the potential shifted from the open-circuit potential to the active direction, a section of concentration polarization resulting from the dissolved oxygen reduction reactions ($\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$) and a section of active polarization resulting from hydrogen gas generation ($2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^-$) appeared. The range that corresponds to the corrosion protection potentials produced by the concentration polarization resulting from dissolved oxygen reduction reactions was identified as -1.37 V to -0.68 V and the current densities in this potential range showed very low values of 10^{-8} – 10^{-5} A/cm^2 . The corrosion protection limit potential which presents the concentration polarization resulting from dissolved oxygen reduction reactions progressed to active polarization was -1.37 V . This concentration polarization resulting from fast oxygen reduction actions at the surface is a phenomenon where current densities are stagnated due to the formation of concentration gradient layers. Since the determination of concentration polarization range is governed by various environments such as flow velocities, temperatures and the concentrations of reacting ions, stable corrosion protection potential range should be established. When compared with the anodic polarization curve, the application of cathodic protection method at the potential of cathodic polarization is considered to be more reasonable rather than that of anodic polarization where the current densities continuously increased without the characteristics of passive states [11].

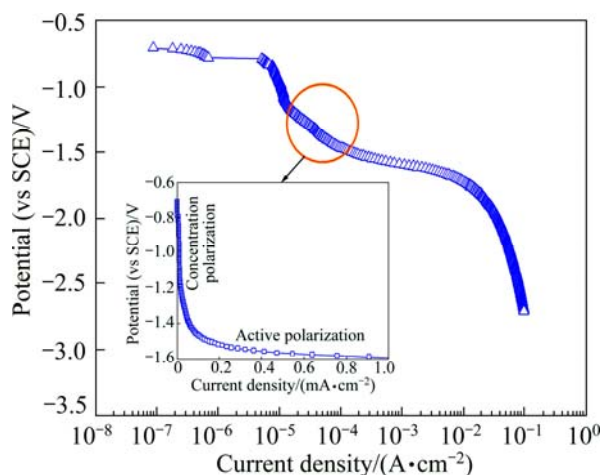


Fig. 4 Cathodic polarization curve of 5052-O Al alloy in seawater

Figure 5 presents a polarization curve for Tafel analysis obtained by polarizing 5052-O Al alloy from the OCP to $\pm 0.25\text{ V}$ in seawater. In Fig. 5, the experiment was conducted three times with the same methods. From the curves of anodic polarization, the current densities continuously increased as the potential increased. However, in the range of cathodic polarization, lower current densities were shown compared with the anodic polarization due to the effect of concentration polarization. The corrosion potential and corrosion current density measured through the Tafel extrapolation method were -682.7 mV and $1.2 \times 10^{-6}\text{ A/cm}^2$, respectively.

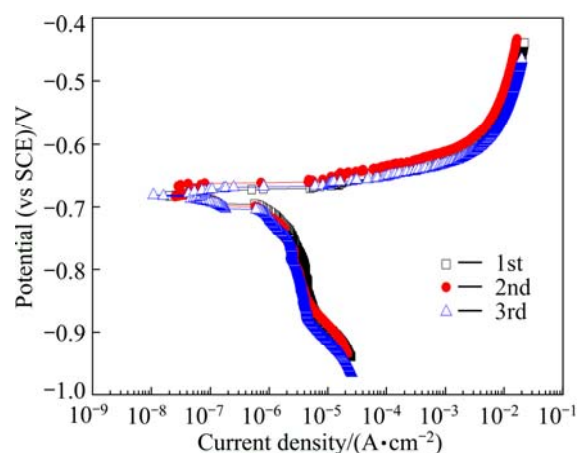


Fig. 5 Polarization curves for Tafel analysis of 5052-O Al alloy in seawater

Figure 6 shows the current density change with time obtained by conducting potentiostatic experiments on the 5052-O Al alloy in seawater. In the potential range of -0.50 to -0.30 V (Fig. 6(a)), generally high current densities were observed in all potential range as reviewed in the anodic polarization curve, and high current density values were shown with the increase of the potential. The current densities in the potential range of -0.65 to -0.55 V (Fig. 6(b)) showed a tendency of rapid increase at the beginning of the immersion. Therefore, stable behaviors showed until the experiment was finished. The current densities in the range of -0.80 to -0.70 V (Fig. 6(c)) rapidly decreased to around 10^{-7} A/cm^2 at the beginning. After immersion of 70 s , the current densities increased. The stable behavior is observed at about 200 s . In potentiodynamic polarization experiments, this range showed a potential close to the open circuit potential, and the lowest current density of $(2\text{--}3) \times 10^{-6}\text{ A/cm}^2$ is among the applied potential of the 5052-O Al alloy. For Figs. 6(d) and (e), the applied potentials were -1.40 to -0.85 V which correspond to the range of concentration polarization resulting from the dissolved oxygen reduction reactions in the cathodic polarization curve. In these ranges, generally stable

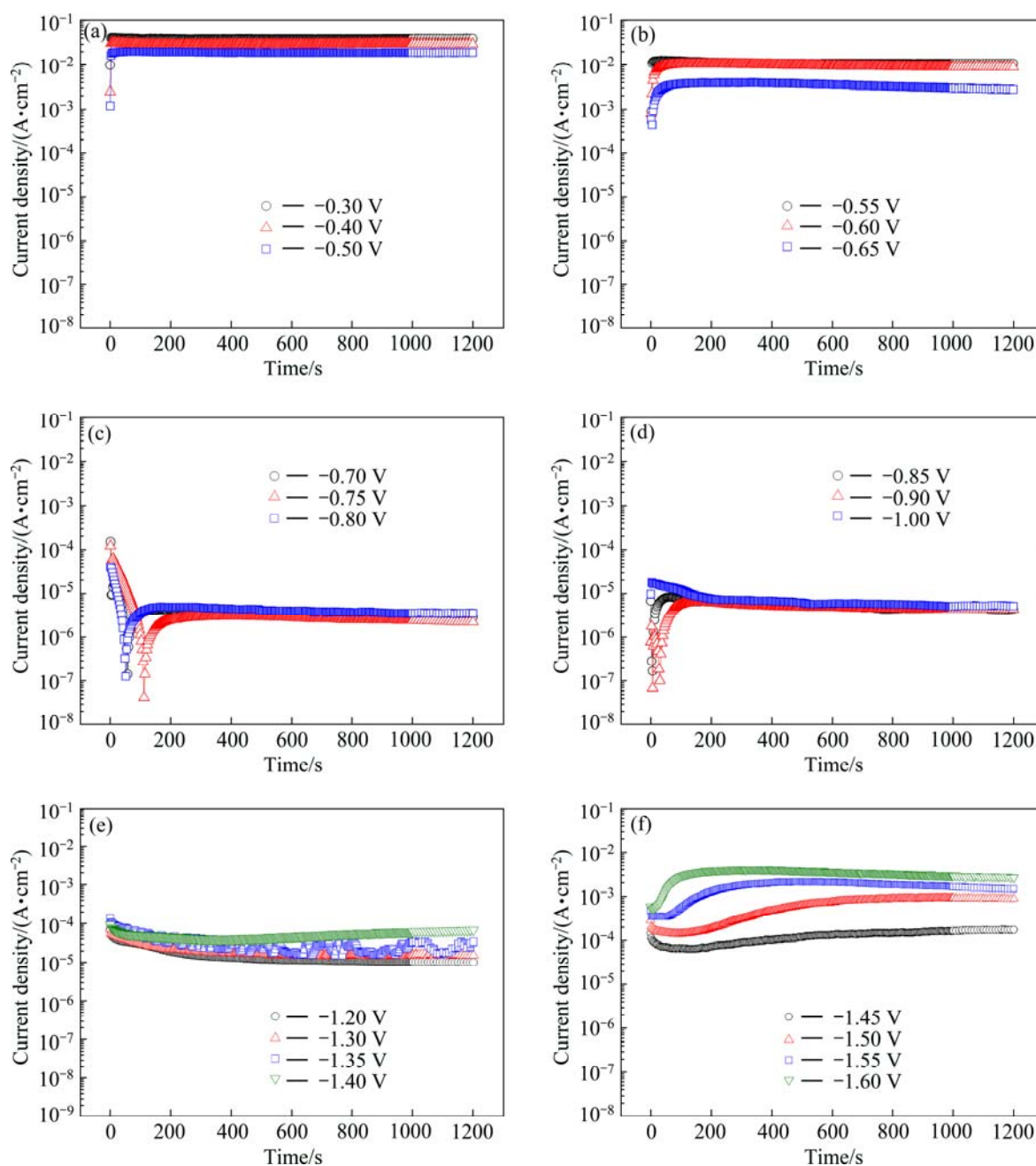


Fig. 6 Time—current density curves of 5052-O Al alloy with various applied potential after potentiostatic experiments in seawater

behaviors were shown and current densities were identified to be relatively low value. The current density at the potential of -1.4 V showed a tendency of slow increase. As reviewed in the cathodic polarization curve, it is considered that the current densities increased under the effect of active polarization from -1.37 V which is a turning point between the concentration polarization due to dissolved oxygen reduction reactions and the active polarization by hydrogen gas generation. In the range of -1.60 to -1.45 V Fig. 6(f) shows a tendency that current densities increased as the potential shifted to the active direction. This is considered to be a result of corrosion rate increasing resulting from the molecular hydrogen

gas generated by the strong reaction of the active polarization [12]. Consequently, based on the results of changes in current densities in relation to the applied potentials, higher or lower potentials beyond the range of -1.30 to -0.70 V showed high current densities. It is considered that the corrosion protection range is -1.3 to -0.70 V, which showed lower current densities in the whole ranges when the cathodic protection method was applied.

Figure 7 presents the surface morphologies of the 5052-O Al alloy after potentiostatic experiments for 1200 s under various potential conditions in seawater. As seen in the potentiostatic experiments, severe corrosion

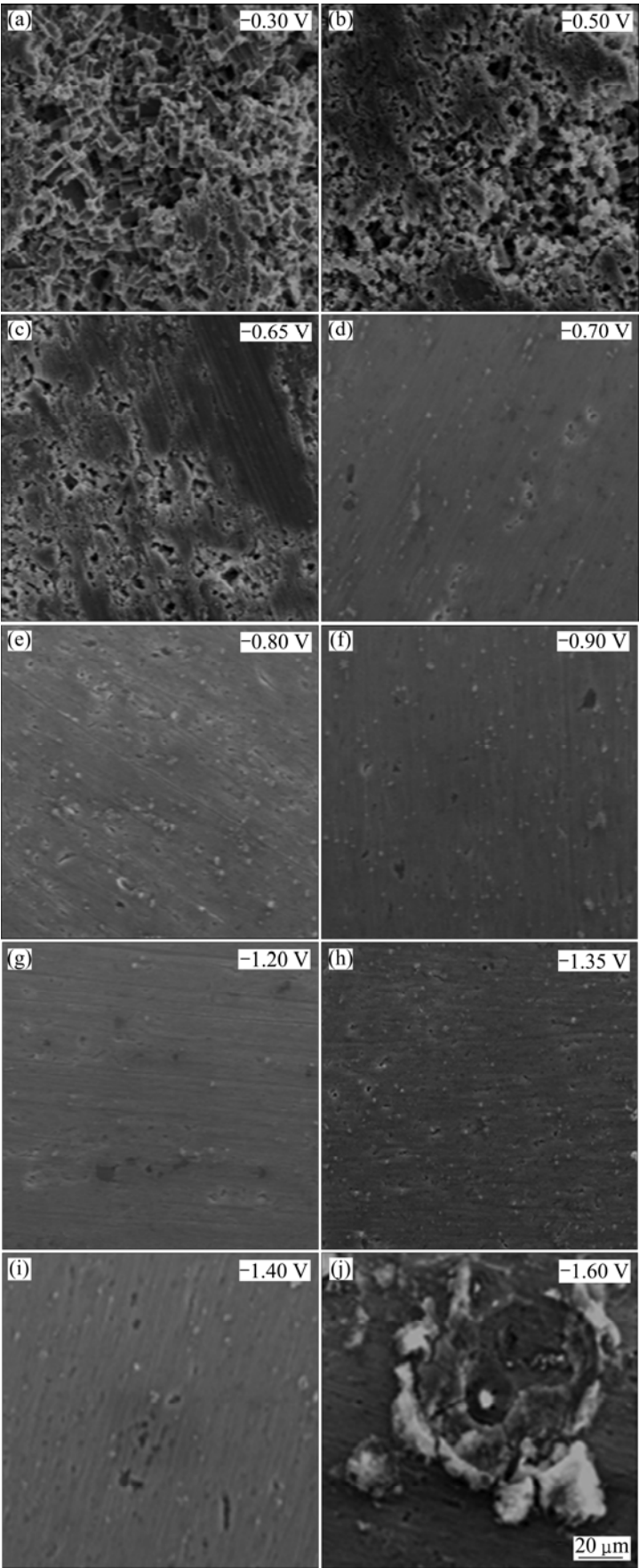


Fig. 7 Surface morphologies of 5052-O Al alloy under various applied potential after potentiostatic experiments for 1200 s in seawater

was observed on the surface of the specimen in the potential range of -0.30 to -0.65 V due to the active dissolution reactions. The dissolution reactions were activated as the potential increased, so the corrosion damage increased. On the other hand, in the potential of -1.30 to -0.70 V, low current densities were shown due to the concentration polarization resulting from the dissolved oxygen reduction reactions. And thus good surfaces with little damage could be observed in general. In the case of -1.40 V which is lower than the turning point of -1.37 V, small damaged areas in the shape of craters can be observed. The damaged areas increased as the potential continuously decreased. Thereafter, the generation of atomic hydrogen progressed to the generation of molecular hydrogen [6]. Furthermore, the matters observed on the surface are electro-deposited films of calcareous deposits of CaCO_3 or $\text{Mg}(\text{OH})_2$ that have been formed by electrochemical reactions during cathodic polarization in seawater. When calcareous deposits formed to be sound, these will work as films with excellent corrosion resistance [13].

4 Conclusions

1) Based on the results of tensile tests, the tensile strength and elongation in rolling direction and vertical direction did not show any significant differences.

2) The natural potentials were quite stable in sea water. However, based on the results of the anodic polarization experiments, there are not obvious passive state characteristics and current densities continuously increased as the potential moved to the noble direction.

3) From the results of cathodic polarization experiments, the phenomenon of concentration polarization due to dissolved oxygen reduction reactions appeared quite clearly and very low current densities were shown in the range of -1.30 to -0.70 V. This range corresponds to the corrosion protection potential range when the cathodic corrosion protection method is applied. The turning point between concentration polarization and activation polarization is considered to be -1.37 V.

4) It is considered that the cathodic corrosion protection method will be more suitable compared with

the anodic protection method for 5052-O Al alloy. The corrosion protection potential range is considered to be in the potential range of -1.30 to -0.70 V.

References

- [1] PARK J C, KIM S J. Mechanical characteristics of cast AC7AV alloy alternative multi-pass friction stir processing [J]. Surface Review and Letters, 2010, 17(1): 69–72.
- [2] KIM S J, KO J Y, HAN M S. Evaluation of the characteristics using slow strain rate tests of 5456 Al–Mg alloy for ship construction [J]. The Korean Journal of Chemical Engineering, 2006, 23(6): 1028–1033.
- [3] JANG S K, HAN M S, KIM S J. Electrochemical characteristics of stainless steel using impressed current cathodic protection in seawater [J]. Transactions of Nonferrous Metals Society of China, 2009, 19: 930–934.
- [4] PARK S H, KIM J S, HAN M S, KIM S J. Corrosion and optimum corrosion protection potential of friction stir welded 5083-O Al alloy for leisure ship [J]. Transactions of Nonferrous Metals Society of China, 2009, 19: 898–903.
- [5] KIM S J, HAN M S, JANG S K. Electrochemical characteristics of Al–Mg alloy in seawater for leisure ship: Stress corrosion cracking and hydrogen embrittlement [J]. The Korean Journal of Chemical Engineering, 2009, 26(1): 250–257.
- [6] JONES D A. Principles and prevention of corrosion [M]. New York: Prentice Hall, 1996: 143–165; 234–289.
- [7] BARD A J, FAULK L R. Electrochemical methods fundamentals and application [M]. New York: John Wiley & Son Inc, 1981: 63.
- [8] KIM S J. Evaluating the electrochemical properties in the protection potential of material for use in Al vessels in seawater [J]. Materials Science Forum, 2006, 510–511: 158–161.
- [9] KIM S J, OKIDO M, MOON K M. The electrochemical study on mechanical and hydrogen embrittlement properties of HAZ part as a function of post-weld heat treatment in SMAW [J]. Surface and Coatings Technology, 2003, 169–170: 163–167.
- [10] KIM S J, JANG S K. A slow strain rate test experiment to evaluate the characteristics of high-strength Al–Mg alloy for application in ships [J]. Materials Science Forum, 2006, 510–511: 162–165.
- [11] KIM S J, HAN M S, KIM S K, JANG S K. Improvement of hydrogen embrittlement and stress corrosion cracking by annealing for Al–4.4Mg–0.6Mn alloy [J]. Transactions of Nonferrous Metals Society of China, 2011, 21: s17–s22.
- [12] KIM S J, JANG S K, KIM J I. Effects of post-weld heat treatment on optimum cathodic protection potential of high-strength steel in marine environment conditions [J]. Materials Science Forum, 2005, 486–478: 133–136.
- [13] HAN M S, KO S C, PARK S H, JANG S K, KIM S J. Optimization of corrosion protection potential for stress corrosion cracking and hydrogen embrittlement for 5083-H112 alloy in seawater [J]. Metals and Materials International, 2008, 14(2): 203–211.

船用 5052-O 铝合金在海水中的力学和电化学性能

Seong-Jong KIM, Seok-Ki JANG, Min-Su HAN, Jae-Cheul PARK, Jae-Yong JEONG, Sang-Ok CHONG

Division of Marine Engineering, Mokpo Maritime University, Haeyangdaehak-ro 91 Mokpo-Si, 530-729, Korea

摘 要: 采用电化学实验和 SEM 表面形貌观察, 对船用 5052-O 铝合金在海水中的腐蚀保护电位进行优化, 以克服诸如点蚀、腐蚀、应力腐蚀开裂和氢脆等行为的发生。在外加电流阴极保护的条件下, 最优的保护电位范围为 -1.3 V~ -0.7 V。在此电位下, 试样的腐蚀电流密度较低, 经恒电位实验后, 试样表面形貌保持得较好。

关键词: 铝合金; 腐蚀; 海水腐蚀; 电化学性能; 应力腐蚀开裂; 氢脆; 阴极保护

(Edited by Sai-qian YUAN)