

Comparison of electrochemical properties of atmospheric pressure plasma coatings for $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ and CoNiCrAlY in sea water

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Abstract: To improve the durability of underwater rotating products, the corrosion characteristics in harsh marine environment were evaluated through various electrochemical experiments on the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ and CoNiCrAlY coating layers by atmospheric pressure plasma spray coating process. By evaluating the corrosion resistance of these materials, their applicability to environmentally friendly power generation equipment such as blades of tidal current turbines was examined. According to the Tafel analysis for micro-areas including the coating layer, the coating/metal interlayer and the base metal, the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer and the CoNiCrAlY coating layer show markedly lower corrosion current density than the base metal. The corrosion current density of the CoNiCrAlY coating layer ($9.75316 \times 10^{-8} \text{ A/cm}^2$) is about 1.6 times more than that of the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer ($6.13139 \times 10^{-8} \text{ A/cm}^2$).

Key words: $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer; CoNiCrAlY coating layer; underwater rotating products; marine environment; corrosion characteristics; atmospheric pressure plasma spray

1 Introduction

The atmospheric pressure plasma spray coating technology is used to improve the durability of products by forming a coating layer on metal surfaces with materials that have excellent qualities than substrate. In particular, it has a very extensive application scope because many different materials can be applied in line with the purpose such as abrasion resistance, cavitation resistance, and corrosion resistance [1,2]. On the other hand, thermal spray coating technology must select spray materials and condition in tune with the purpose because it is affected by various factors during the process. The spray materials used in this study were the ceramic powder $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ and the thermal barrier coating material CoNiCrAlY. Ceramic materials such as $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ have excellent chemical stability and mechanical characteristics such as high hardness and abrasion resistance. However, as they have high

brittleness, the strength and bonding characteristics of the coating layer are low. However, CoNiCrAlY improves the surface characteristics such as corrosion resistance and abrasion resistance in a high temperature oxidation and corrosion environment [3,4]. This investigation intended to confirm the applicability of these high quality materials to harsh marine environment. Furthermore, to improve the durability of underwater rotating products, the corrosion characteristics in harsh marine environment were evaluated through various electrochemical experiments on the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ and CoNiCrAlY coating layers.

2 Experimental

In this study, the ALBC3 alloy with excellent durability in seawater solution was used as the base metal, the ceramic powder $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ and the thermal barrier coating material CoNiCrAlY were used as the coating materials. By evaluating the corrosion

resistance of these materials, their applicability to environmentally friendly power generation equipment such as blades of tidal current turbines was examined. The chemical compositions of the used base metal and coating materials are listed in Tables 1, 2 and 3. To make identical roughness of the base metal surfaces, they were polished with emery paper No.600. For atmospheric plasma coating, the optimal conditions were applied to each material as shown in Table 4. Furthermore, the more detailed corrosion resistances of the Al_2O_3 -3TiO₂ and CoNiCrAlY coatings will be analyzed more clearly later through potentiostatic and dynamic polarizations, EIS, and micro electrochemical experiments for micro-areas. The potential trends of ALBC3 alloy and coated specimens were measured over 86400 s in natural seawater. The anodic and cathodic polarization was made commencing from the open circuit potential to +3.0 and -2.0 V (vs SCE), respectively, at a scan rate of 2 mV/s at room temperature after immersion for 600 s.

Table 1 Chemical composition of ALBC3 alloy (mass fraction, %)

Al	Fe	Ni	Zn
9.30	3.66	4.39	0.34
Sn	Pb	Si	Mn
0.01	0.013	0.17	0.55

Table 2 Chemical composition of Al_2O_3 -3TiO₂ (mass fraction, %)

Al_2O_3	TiO ₂	SiO ₂	Fe ₂ O ₃
95.4–98.0	≤0.50	≤0.60	2.0–3.5

Table 3 Chemical composition of CoNiCrAlY (mass fraction, %)

Co	Ni	Cr	Al	Y
35.35–41.65	31.0–33.0	20.0–22.0	7.0–9.0	0.35–0.65

Table 4 Spray conditions of atmospheric pressure plasma coating for Al_2O_3 -3TiO₂ and CoNiCrAlY

Parameter	Al_2O_3 -3TiO ₂	CoNiCrAlY
Argon/(L·min ⁻¹)	38	65
Spray distance/mm	120	140
Feed rate/(g·min ⁻¹)	50	40
Hydrogen/(L·min ⁻¹)	14	14
Current/A	600	600
Powder gas/(L·min ⁻¹)	3.2	2.3
Injector angle/(°)	90	90
Traverse speed/(mm·s ⁻¹)	8	8

The polarization system consisted of a Pt coil, which acted as a counter electrode, and an Ag/AgCl saturated KCl as the reference electrode. The potentiostatic experiment was conducted for 3600 s under various applied potentials to compare changes of current density with time, and compare the degrees of corrosion. Additionally, the polarization resistance (R_p) was assessed by performing electrochemical impedance spectroscopy (EIS) to investigate the corrosion resistance for base metal and coating layers. Furthermore, micro-electrochemical experiments was conducted to evaluate the electrochemical characteristics for the coated layer, interlayer and substrate of local area on the cross-section using droplet cells, and the set-up of the droplet cells used in the experiment are shown in Fig. 1 [5–7]. The droplet cells use saturated calomel electrodes as reference electrodes and platinum conducting wires pass through the inside of the capillaries to be connected to the counter electrode. When the capillary tips come into contact with specimens, only the areas exposed to the internal electrolyte solution work as the areas of working electrodes to compose electrochemical cells. In order to expose the areas of working electrodes in micro units, the diameters of the capillary tips were made to be about 150 μm and exposed areas during the electrochemical experiment were measured down to six places of decimals. In the micro electrochemical experiment, the tendencies of polarization with the basic of the open-circuit potential (φ_{oc}) from -0.25 V to +2.5 V in the local area were analyzed. The average corrosion current densities and average corrosion potentials obtained through the Tafel analysis were compared.

3 Results and discussion

Figure 2 shows the natural potential measurement results over time for 86400 s for ALBC3 alloy and APS coated specimens in natural seawater solution. In general, both the Al_2O_3 -3TiO₂ and CoNiCrAlY coatings exhibit nobler potential compared to the ALBC3 base metal. The ALBC3 alloy repeated rising and falling in a very narrow range of -0.218 V to -0.198 V in the early stage of immersion. They showed the potential of -0.219 V at around 20000 s, and maintained stable behavior until the end of the experiment. On the other hand, the potential of the Al_2O_3 -3TiO₂ coating layer decreased from -0.1096 V to -0.154 V until about 13000 s at a constant slope in the early stage of immersion. Then it stabilized until 25500 s. After that, it rose to a little noble potential and maintained stabilized condition until about 77000 s, but it showed unstable variations again. The reason for this is that unlike the base metal, lamellar shaped volumes are laminated on the surface of the coating layer, and there

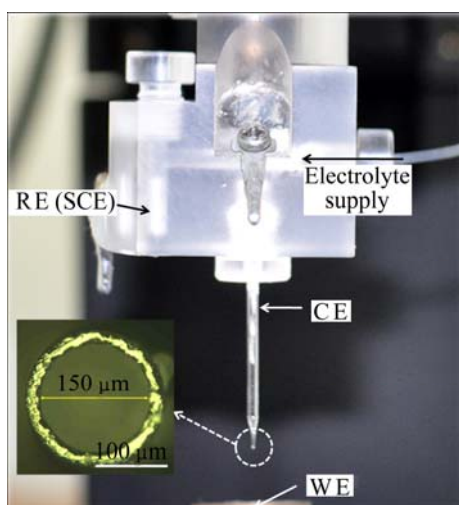


Fig. 1 Set-up of micro droplet-cell and micrograph of capillary tip (RE denotes reference electrode, CE denotes counter electrode, WE denotes electrode)

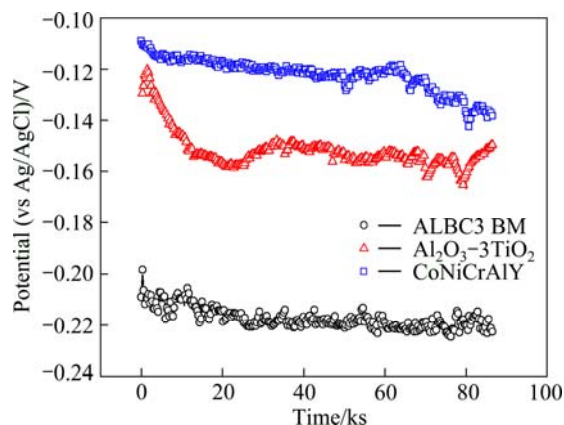


Fig. 2 Curves of potential vs time for ALBC3 alloy and APS coating layers

are voids and open pores formed between the layers. These defects play the role of a penetration route for electrolytic solution at the electrochemical aspect [8]. Then, when the electrolytic solution penetrates into the base metal, micro-galvanic cells are formed between the coating and interlayer, and between the interlayer and the base metal. As a result, the coating layer decreases corrosion resistance effect and can be separated by causing the corrosion of base metal or lowering the adhesive strength of the interlayer. The defects formed inside the coating layer provide a penetration route for electrolytic solution. It seems to have caused somewhat unstable variations of potential [9]. On the other hand, the CoNiCrAlY coating layer exhibits nobler potential than the base metal and the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating, and shows very stable tendency from the early stage of immersion until about 62000 s. After that, the potential tends to slowly move in the active direction, and the decrease of potential not great. Thus, it can be concluded that the corrosion resistance effects of the $\text{Al}_2\text{O}_3\text{-3TiO}_2$

and CoNiCrAlY coating layers would be excellent when compact coating layer is formed as the coating layers showed considerably nobler potential than the base metal. However, when plasma spray process is performed in the atmosphere with no vacuum environment, the impurities and gases from the outside are absorbed at high temperatures. In this case, when they exist in the coating layer as defects, it will cause unstable corrosion resistance characteristics [10].

Figure 3 compares the anodic polarization behavior of the ALBC3 alloy and APS-coated specimens in natural seawater solution. The open circuit potential (ϕ_{oc}) of the ALBC3 alloy is -0.207 V. As the anodic polarization progresses, the passivation characteristic of decreasing current density appears at 0.137 V (ϕ_p). However, as the measured passive critical current density (J_p) is very high at 0.01403 A/cm², it cannot be applied as anodic corrosion protection method. The reason that passivation formation is observed in the anodic polarization behavior of the ALBC3 alloy is that the matters form by oxidation reaction on the surface. The Al and Ni elements added to the base metal have the characteristic for forming and restoring of sound passivation. For the passivation section of the ALBC3 alloy, oxidation matters are removed by the oxygen generated with continuous dissolution reaction and the de-lamination of oxidation matters or pitting corrosion occurs by the penetration of chlorine ions. This pitting corrosion (ϕ_i) is measured at 1.182 V, and the current density rapidly increases larger than this potential. On the other hand, for the APS-coated specimen, the variation of current density with potential is very low compared to the ALBC3 base metal. In particular, current density steadily increases with potential larger than the open circuit potential ($\phi_{oc} = -0.037$ V) of the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating, showing no characteristic of passivation for formation and restoration. For the passivation section of the ALBC3 alloy, the oxidation matters are removed by the oxygen generated with continuous dissolution reaction and the de-lamination of oxidation matters or pitting corrosion occurs by the penetration of chlorine ions. This pitting corrosion (ϕ_i) is measured at 1.182 V, and the current density rapidly increases after this potential. On the other hand, for the APS-coated specimen, the variation of current density with potential is very low compared to the ALBC3 base metal. In particular, the current density steadily increases with potential larger than the open circuit potential ($\phi_{oc} = -0.037$ V) of the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating, and no passivation characteristics are observed. However, it shows considerably lower current density than the base metal, because the main chemical Al_2O_3 of the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating layer is an insulator. Chemicals with such insulation characteristics have very good

corrosion resistance because it interferes with the flow of current generated by voltage in the electrochemical cell [11]. The increase of current density of the CoNiCrAlY coating layer according to potential variation is a little lower than that of the base metal. However, it shows very high current density compared to the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating, and passivation is not observed at all. Consequently, the CoNiCrAlY coating layer shows weaker corrosion resistance than $\text{Al}_2\text{O}_3\text{-3TiO}_2$ during anodic polarization. These defects are the penetration route by the inclusion of impurities during the flight of melting splats in the APS spraying, the pores between the laminated layers and the defects due to the thermal history during cooling at high temperature [10,13]. In other words, as the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating layer has relatively many pores and defects, the penetration of electrolytic solution is easy during long-term immersion. So, it shows the combined potential of the coating layer and the base metal at the interface. During the anodic polarization, however, the CoNiCrAlY coating layer causes more dissolution reaction under the reversible environment, and shows relatively higher current density.

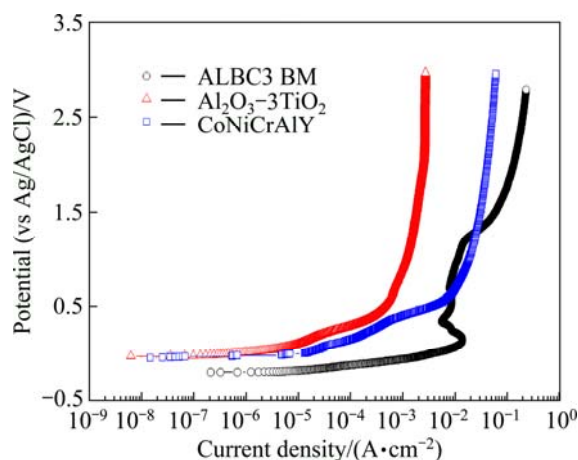


Fig. 3 Comparison of anodic polarization trends for ALBC3 alloy and APS coating layers

Figure 4 presents the cathodic polarization behavior of the ALBC3 alloy and APS-coated specimens in natural seawater solution. The ALBC3 alloy shows a rapidly increasing trend of the current density with the decrease of potential as the ions uniformly distribute in areas close to the surface of the working electrode due to slow reduction rate after the open-circuit potential (-0.208 V). At around -0.45 V, however, the reduction rate of oxygen increases on the working electrode surface and the current density slows down as the oxygen ions are quickly consumed in the area close to the surface of ALBC3 alloy. This is the concentration polarization due to the dissolved oxygen reduction reaction and an electrochemical reaction that is

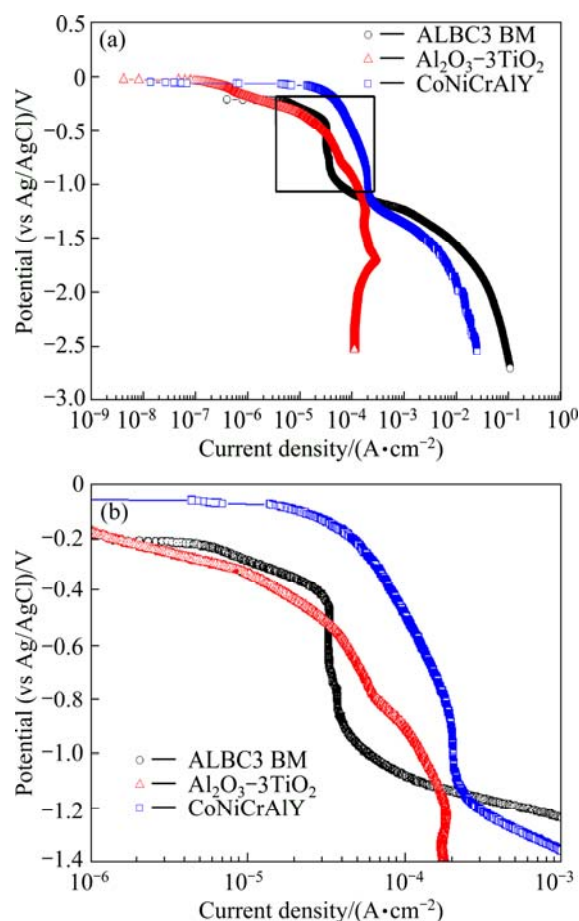


Fig. 4 Comparison of cathodic polarization trends for ALBC3 alloy and APS coating layers

dominated by the diffusion of oxygen in seawater solution. This polarization is caused by the concentration difference between the working electrode surface and in the electrolytic solution. Concentration polarization is dominated by the diffusion rate of ions toward the metal surface as the concentration of oxygen ions in the solution is limited. When the reduction rate is fast, the current density reaches and stays at the limiting diffusion current density (J_l). This limiting diffusion current density is affected by the diffusion coefficient, such as the concentration of reacting ions in solution, and the thickness of the diffusion layer. This is a very important behavior in the reduction process [12]. The concentration polarization range of the ALBC3 alloy is from -0.45 V to -1.0 V. The J_l in this case is approximately in the range from 3.35×10^{-5} to 5.86×10^{-5} A/cm². Thus, with the concentration polarization, the concentration of oxygen ions on the surface rapidly decreases by fast reduction rate and slows down the corrosion reaction. This potential range allows cathodic protection method in seawater environment, and it is used as a corrosion resistance system for marine structures as impressed current cathodic protection (ICCP) system. After the concentration polarization the activation polarization

occurs at the potential below -1.0 V and the current density sharply increases again. The APS-coated specimens show a little different behavior compared to the base metal. The CoNiCrAlY coating shows a higher current density than the base metal from the open circuit potential to -1.15 V. This range corresponds to the concentration polarization section and seems to present higher corrosion reaction than the base metal. After that in the activation polarization area, it shows relatively lower values. On the other hand, the Al_2O_3 -3TiO₂ coating layer only shows concentration polarization after the open circuit potential and the current density gradually decreases along with the decreasing potential. Although activation polarization must be more conspicuous below -1.68 V, the current density decreases further and stays at 1.149×10^{-4} A/cm². Consequently, the application of the Al_2O_3 -3TiO₂ and CoNiCrAlY coating technology will show better corrosion resistance than the base metal.

Figure 5 compares the Bode plot and Nyquist plot which are the EIS analysis results for the ALBC3 alloy and APS-coated specimens in natural seawater solution. The surface of metals exposed to corrosive environment consists of oxides, chlorides, and hydroxides. In the case of ALBC3 alloy, its corrosion resistance is improved by forming corrosion products on surface such as cuprous oxide (Cu_2O). As shown in Fig. 5(a), the specimen

coated with Al_2O_3 -3TiO₂ shows the highest polarization resistance in the Bode plot and the CoNiCrAlY coating shows a similar polarization resistance as the ALBC3 alloy. This result brings out a striking difference in the electro-kinetic potential polarization result that presents lower current density than substrate. The reason for relatively low corrosion resistance of the CoNiCrAlY coating layer appears to be that the electrolytic solution could easily penetrate as there are many pores and capillary cracks in the coating layer [13]. The EIS analysis finds very weak corrosion resistance of the CoNiCrAlY coating compared to the Al_2O_3 -3TiO₂ coating. The reason for this seems to be that when corrosion occurs on the coating surface in various ways, the movement of electric charge is interfered by the oxides that are formed on the surface. It seems that the Al_2O_3 -3TiO₂ coating shows high corrosion resistance because it consists of Al_2O_3 compounds and the movement of electric charge is limited on the surface that has no corrosion damages. Furthermore, the Nyquist plot in Fig. 5(b) also shows the same tendency, but CoNiCrAlY shows a little higher corrosion resistance than the ALBC3 alloy due to the Warburg parameter response resulting from diffusion.

Figure 6 shows the variation of current density over time after a potentiostatic experiment during 3600 s for the Al_2O_3 -3TiO₂ and CoNiCrAlY coating layers in

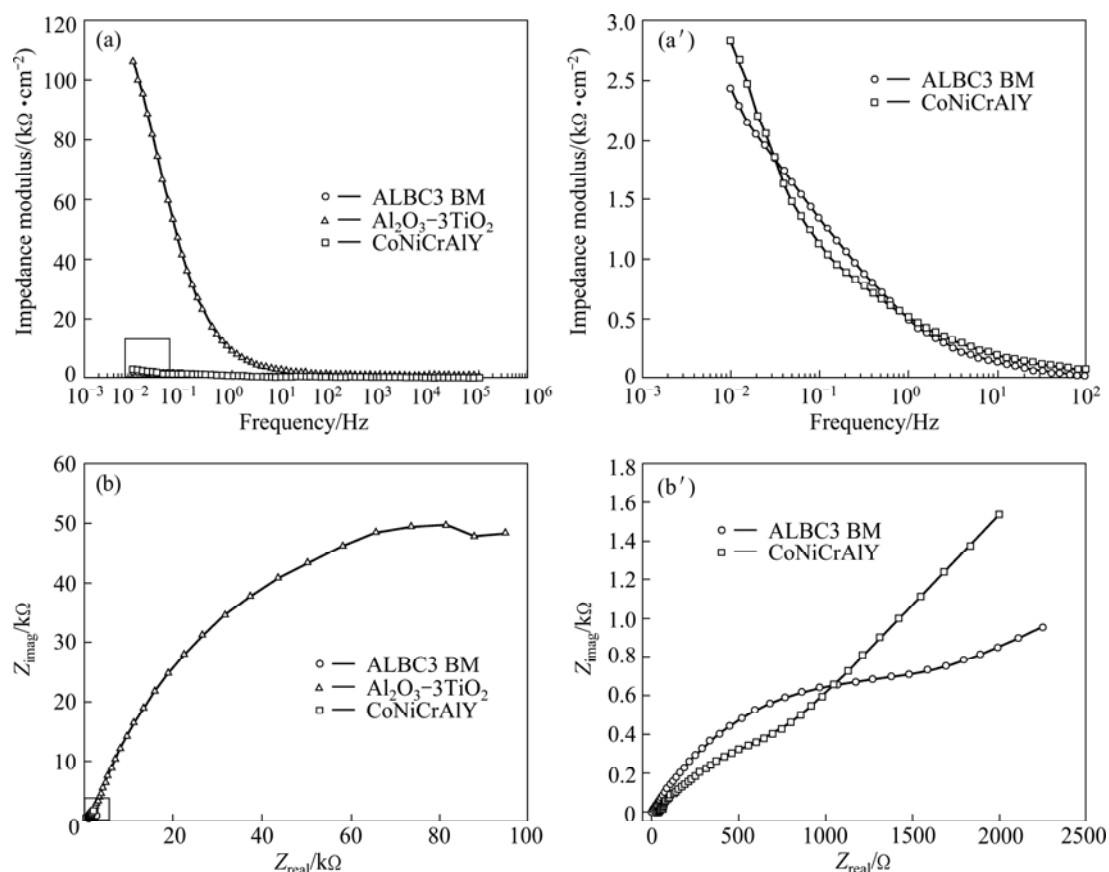


Fig. 5 Comparison of EIS results for ALBC3 alloy and HVOF coating layers in sea water: (a), (a') Bode plot; (b), (b') Nyquist plot

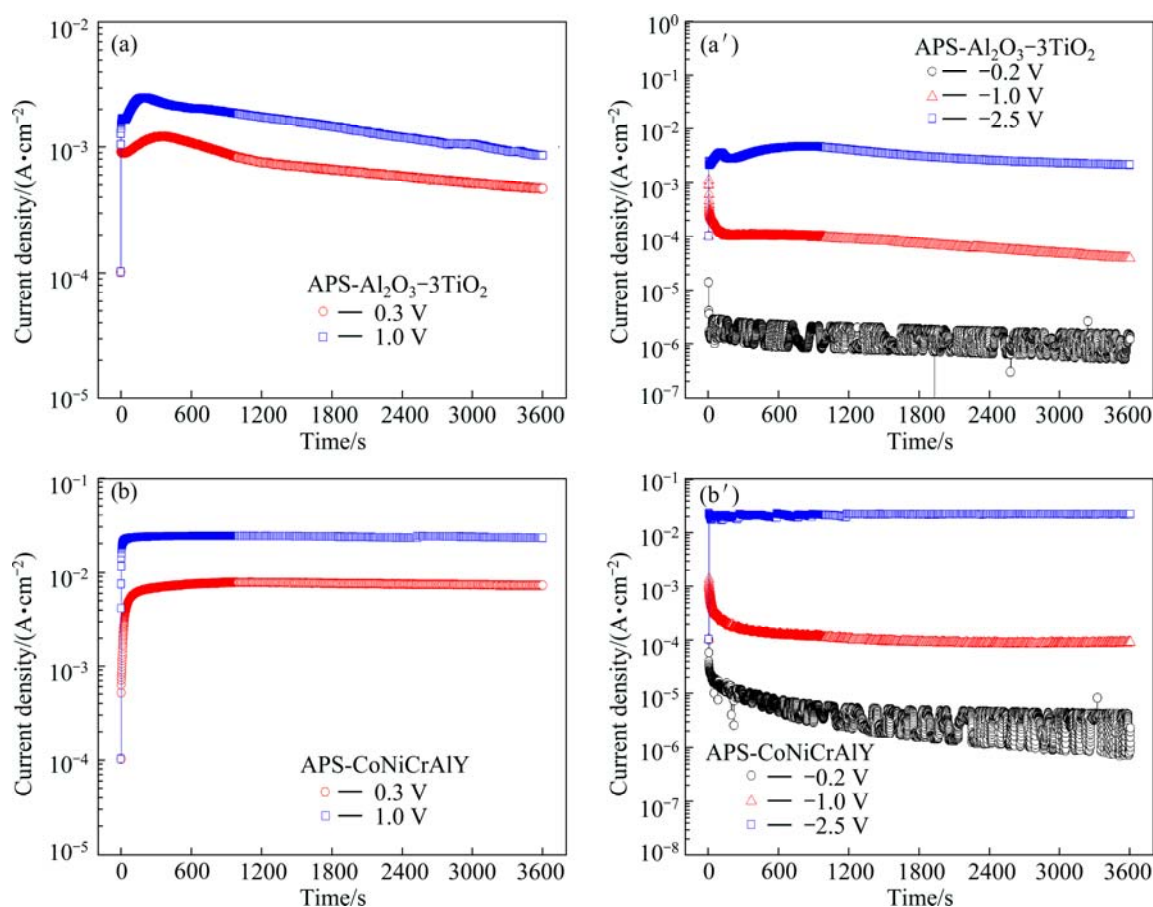


Fig. 6 Potentiostatic experiments for $\text{Al}_2\text{O}_3\text{-3TiO}_2$ (a, a') and CoNiCrAlY coatings (b, b') in sea water

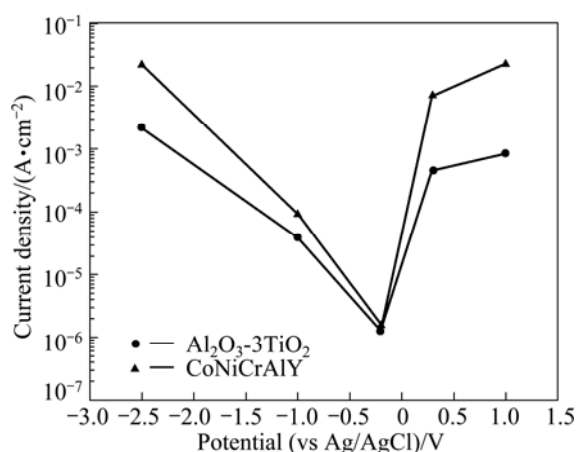
natural seawater solution. The potentiostatic experiment is good for evaluation of corrosion resistance as it evaluates detailed corrosion characteristics and compares the current density at constant potential within the same duration. Thus, it is needed to evaluate more detailed corrosion characteristics for the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ and CoNiCrAlY coating layers which are applied to the APS coating technology. In this study the same potential condition was selected and the corrosion resistance characteristics were compared by comparing the current density under each potential condition. Both coating materials show similar overall tendency for the applied potential. The $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating in Fig. 6(a) increases from 200 s to 400 s in the early stage of the experiment and then tends to keep decreasing until the end of the experiment at 0.3 V and 1.0 V. The current density at the end of the experiment is $4.69 \times 10^{-4} \text{ A/cm}^2$ and $8.54 \times 10^{-4} \text{ A/cm}^2$, respectively, and the higher the potential is, the greater the current density becomes. In the potential range of -0.25 V and -1.0 V , it shows a stable tendency until the end of the experiment. At 3600 s, the current densities are $2.15 \times 10^{-3} \text{ A/cm}^2$ and $3.97 \times 10^{-5} \text{ A/cm}^2$, respectively. At the applied potential of -0.2 V , however, the variations of current density are very large and it repeatedly rises and falls. This phenomenon is that the

oxidation and reduction reactions occur simultaneously in local areas near the equilibrium potential. The current density at this potential is very low at $1.24 \times 10^{-6} \text{ A/cm}^2$. Meanwhile the CoNiCrAlY coating layer in Fig. 6(b) quickly moves in the noble direction at 0.3 V and 1.0 V in the early stage of experiment and shows stable behavior at a very high current density until the end of experiment. At the potential of -2.5 V , the current density is very high due to the activation polarization. As the applied potential is close to ϕ_{oc} , the current density tends to decrease. At the potential of -0.2 V , the current density becomes very low at $1.53 \times 10^{-6} \text{ A/cm}^2$, and it repeatedly rises and falls. The current density values at the end of experiment for each potential condition are detailed in Table 5.

Figure 7 shows the tendency of current density at each applied potential at the end of the potentiostatic experiment during 3600 s for the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ and CoNiCrAlY coating layers. At all the potentials applied, the CoNiCrAlY coating shows higher current density than the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ coating. In particular, the difference in current density rapidly increases in the activation polarization (-2.5 V) and activation dissolution reaction (1.0 V) parts. Consequently, the CoNiCrAlY coating appears to have lower corrosion

Table 5 Current densities at end of potentiostatic experiments for $\text{Al}_2\text{O}_3\text{-3TiO}_2$ and CoNiCrAlY coatings

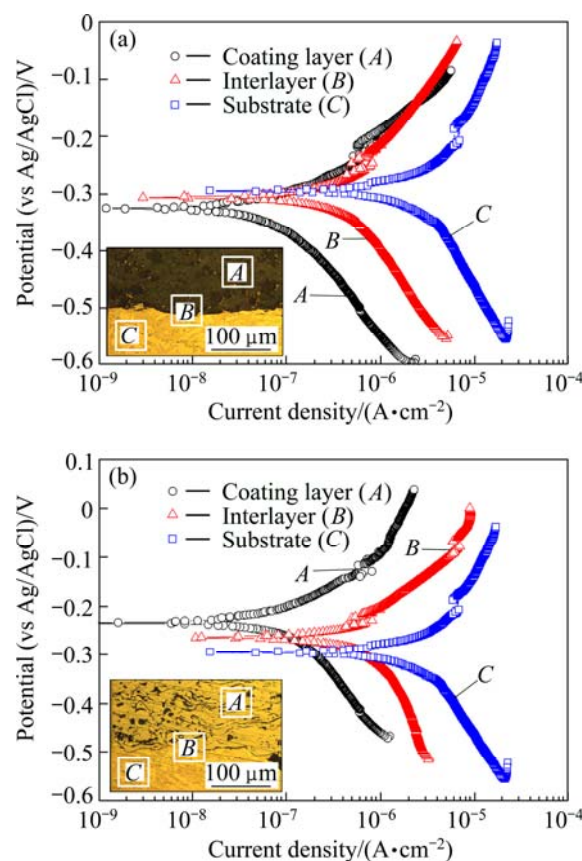
Potential (vs Ag/AgCl)/V	Current density/($\text{A}\cdot\text{cm}^{-2}$)	
	$\text{Al}_2\text{O}_3\text{-3TiO}_2$	CoNiCrAlY
-2.5	2.15×10^{-3}	2.19×10^{-2}
-1.0	3.97×10^{-5}	9.03×10^{-5}
-0.2	1.24×10^{-6}	1.53×10^{-6}
0.3	4.69×10^{-4}	7.25×10^{-3}
1.0	8.54×10^{-4}	2.30×10^{-2}

**Fig. 7** Comparison of current density at end of potentiostatic experiments

resistance due to activation polarization and dissolution reaction, which corresponds to the results of the EIS experiment described above.

Figure 8 shows the polarization behavior for Tafel analysis for the micro-areas of the cross-sections of the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ and CoNiCrAlY coatings including the coating layer, coating/base metal interface and the metal using micro-droplet cells. For the experiment areas, after polishing the cross-sections of the coated specimens, the capillary tip contacts with the coating layer (A), the coating/base metal interlayer (B), and the base metal (C). For the coating/base metal interlayer, they are exposed at the equal ratio of area by positioning the capillary of the micro-droplet cells at the center. Furthermore, as the electrochemical behavior at the micro-areas using the micro-droplet cells appears in various ways depending on the distributions of pores, oxides, and various elements, three or more experiments were performed for each area to improve reliability. Firstly, in the case of $\text{Al}_2\text{O}_3\text{-3TiO}_2$ in Fig. 8(a), the corrosion current density

of the coating layer is $6.13139\times 10^{-8} \text{ A/cm}^2$ which is 1/45 of that of the base metal. On the other hand, the corrosion current density of the coating/base metal interlayer measured at $3.6061\times 10^{-7} \text{ A/cm}^2$ which is approximately 6 times as that of the coating layer and 1/8 of that of the base metal. For CoNiCrAlY in Fig. 8(b), the corrosion current density of the coating layer is $9.75316\times 10^{-8} \text{ A/cm}^2$, which is 1/28 of that of the base metal, and the value of the coating/base metal interlayer is 1/7 of that of the base metal. Thus, the corrosion current density at each interlayer appears to be the mixed potential of the coating layer and the base metal. The corrosion current density of the coating layers are 1/45 and 1/28 of that of the base metal, respectively. It is predicted that CoNiCrAlY will have a corrosion current density that is about 1.6 times as that of $\text{Al}_2\text{O}_3\text{-3TiO}_2$. The details of the Tafel analysis results for the $\text{Al}_2\text{O}_3\text{-3TiO}_2$ and CoNiCrAlY coating layers, interlayers, and the base metal are shown in Table 6.

**Fig. 8** Comparison of Tafel analysis curves using micro-droplet cell at local area: (a) $\text{Al}_2\text{O}_3\text{-3TiO}_2$; (b) CoNiCrAlY **Table 6** Tafel analysis for local area of cross-section on coating layers using micro-droplet cell

Area	Corrosion potential/V			Corrosion current density/($\text{A}\cdot\text{cm}^{-2}$)		
	$\text{Al}_2\text{O}_3\text{-3TiO}_2$	CoNiCrAlY	Substrate	$\text{Al}_2\text{O}_3\text{-3TiO}_2$	CoNiCrAlY	Substrate
Coating layer	-0.319	-0.217	-0.295	6.13139×10^{-8}	9.75316×10^{-8}	2.71131×10^{-6}
Interlayer	-0.307	-0.258		3.6061×10^{-7}	3.85313×10^{-7}	

4 Conclusions

1) The natural potential shows that the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ and CoNiCrAlY coating layers have very noble potentials compared to the ALBC3 alloy.

2) The anodic and cathodic experiments show that the CoNiCrAlY coating layer shows a higher current density than the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer during polarization, and no passivation is observed. In contrast, the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer shows very good corrosion resistance as it contains insulation compounds.

3) The potentiostatic experiment found that the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer has lower corrosion current density at all potentials than the CoNiCrAlY coating layer. As a result, the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ spray material is found to be more appropriate for improvement of corrosion resistance of the ALBC3 alloy when using the atmospheric plasma technology for coating.

4) At the Tafel analysis for micro-areas including the coating layer, the coating/metal interlayer and the base metal, the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer and the CoNiCrAlY coating layer shows markedly lower corrosion current density than the base metal: their corrosion current density values are only 1/45 and 1/28 of that of the base metal. Furthermore, the coating/metal interlayer shows a corrosion current density that is in the middle between the coating layer and the base metal. The corrosion current density of the CoNiCrAlY coating layer is about 1.6 times as that of the $\text{Al}_2\text{O}_3\text{--}3\text{TiO}_2$ coating layer.

References

- [1] GUILMANY J M, ESPALLARGAS N, SUEGAMA P H, Benedetti A V. Comparative study of $\text{Cr}_3\text{C}_2\text{--NiCr}$ coatings obtained by HVOF and hard chromium coatings [J]. *Corrosion Science*, 2006, 48: 2998–3013.
- [2] SUEGAMA P H, FUGIVARA C S, BENEDETTI A V, GUILMANY J M, FERNÁNDEZ J, DELGADO J. The influence of gun transverse speed in electrochemical behaviour of thermally sprayed $\text{Cr}_3\text{C}_2\text{--NiCr}$ coatings in 0.5M H_2SO_4 solution [J]. *Electrochimica Acta*, 2004, 49: 627–634.
- [3] AFRASIABI A, SAREMI M, KOBAYASHI A. A comparative study on hot corrosion resistance of three types of thermal barrier coatings: YSZ, YSZ+ Al_2O_3 and YSZ/ Al_2O_3 [J]. *Materials Science and Engineering A*, 2009, 478: 264–269.
- [4] RICHER P, ZÚÑIGA A, YANDOUZI M, JODOIN B. CoNiCrAlY microstructural change induced during cold gas dynamic spraying [J]. *Surface & Coatings Technology*, 2008, 203: 364–371.
- [5] HA H Y, PARK C J, KWON H S. Effects of non-metallic inclusions on the initiation of pitting corrosion in 11% Cr ferritic stainless steel examined by micro-droplet cell [J]. *Corrosion Science*, 2007, 49: 1266–1275.
- [6] KIM J J, LEE J B. A study on the initiation of pitting corrosion of Fe-17Cr alloy using micro-droplet cell technique [J]. *Journal of the Korea Institute of Metals and Materials*, 2008, 46(12): 809–816.
- [7] LOHRENGEL M M, MOEHRING A, PILASKI M. Capillary-base droplet cells: Limits and new aspects [J]. *Electrochimica Acta*, 2001, 47: 137–141.
- [8] KIM S J, LEE S J. Anticorrosion characteristics of a Zn-primer coating in ballast tank under various chloride concentrations [J]. *Physica Scripta*, 2010, 139: 014034.
- [9] RICHER P, YANDOUZI M, BEAUVAIS L, JODOIN B. Oxidation behavior of CoNiCrAlY bond coats produced by plasma. HVOF and cold gas dynamic spraying [J]. *Surface & Coatings Technology*, 2010, 204: 3962–3974.
- [10] MONTICELLI C, BALBO A, ZUCCHI F. Corrosion and tribocorrosion behaviour of thermally sprayed ceramic coatings on steel [J]. *Surface & Coatings Technology*, 2011, 205: 3683–3691.
- [11] KIM S J, WOO Y B. Coating layer and corrosion protection characteristics in sea water with various thermal spray coating materials for STS 304 [J]. *Surface Review and Letters*, 2010, 17(3): 299–305.
- [12] JONES D A. Principles and prevention of corrosion [M]. 2nd Ed. Prentice-Hall, 1996: 80–97.
- [13] LISCANO S, GIL L, STAIA M H. Effect of sealing treatment on the corrosion resistance of thermal-sprayed ceramic coatings [J]. *Surface & Coating Technology*, 2004, 188–189: 135–139.

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