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A comparison study of passive characterization of CoCrNi medium-entropy alloy and CoCrFeNi high-entropy alloy in Na₂CO₃/NaHCO₃ solution

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A comparison of passive characterization of CoCrNi medium-entropy alloy (MEA) and CoCrFeNi highentropy alloy (HEA) was investigated by a series of corrosion tests in Na₂CO₃/NaHCO₃ solution. Both the two alloys exhibit secondary passivation characteristics. The MEA shows a lower passive current density (i_p) in the primary passive region and a higher i_p in the secondary passive zone, compared to the HEA. Moreover, the anti-corrosion property of the two alloys at higher passive potential is weakened, as revealed by low film resistance and high carrier densities. The increase in potential is unfavourable for the formation of a stable and thick passive film, which reduces the protection of the film. Compared with the HEA, the protective performance of passive film grown on the MEA is superior in the primary passive region but inferior in the secondary passive region.

Keywords: MEA, HEA, Passive characterization, Corrosion resistance.

1. INTRODUCTION

Nowadays, a novel design concept of equiatomic or nearly-equiatomic elements alloys has aroused widespread discussion. These materials are called entropy-based alloys, including mediumentropy alloys (MEAs) and high-entropy alloys (HEAs). Since they were originally designed by Yeh et al. [1], they have received extensive attention from the scientific community due to their unique compositional and structural features. Because multiple principal elements function in this type of alloy system, it breaks the limitation of conventional alloys containing one or two main elements, which creates great possibilities for the design of new materials. Traditional alloys are based on a single principal component no longer meet the practical requirements in some cases. Up to now, numerous studies on entropy-based alloys have been reported in recent years, such as CoCrNi MEA and CoCrFeMnNi HEA with a single face-centered cubic (FCC) structure [2]. Co₃₆Fe₃₆Cr₁₈Ni₁₀ alloy containing twins and stacking faults [3], and dual-phase structural Cr₂₀Mn₆Fe₃₄Co₃₄Ni₆ [4] show the outstanding tensile strength, wear-resistance as well as fracture toughness, compared with those of conventional metallic alloys [5-8].

However, in addition to mechanical properties, corrosion performance is also critical to consolidate practical engineering applications of entropy-based alloys. A few investigations on the corrosion behavior of CoCrNi MEA and CoCrFeNi HEA have reported. Mohamed et al. [9] revealed the corrosion behavior of CoCrNi MEA, showing that CoCrNi thin films exhibit superior anti-corrosion performance compared with mild steel in 3.5 wt% NaCl solution. Lv et al. [10] investigated that the grain refinement of the CoCrNi MEA facilitated the formation of thicker passive film, which promoted the anti-corrosion property in 0.1 M NaCl solution. Shang et al. [11] studied the electrochemical behavior and corrosion characteristics of NiCoCr and NiCoFeCr, demonstrating the crucial effect of solid soluted Cr on the corrosion resistance of HEAs, because of the formation of Cr₂O₃, which is highly stable and compact. Cobalt, chromium, nickel and iron are important transition metals which have been commonly employed in many alloys. Also, they act as the dominant element of alloys or additive element that promote their properties. The effect of Co on the corrosion behavior of Co_xCrCuFeMnNi HEAs has been studied by Zhao et al. [12]. The results showed that the thickness and resistance of the passive film of the HEA increased with increasing Co content. Coutu et al. [13] investigated that it was possible to improve the anti-corrosion performance of the Ni₅₀Fe₅₀ alloy by adding a small amount of chromium. Thus, the novel multi-component alloys with high contents of Co and Cr are the key contributors to their remarkable anti-corrosion resistance. In addition, the stability of the film grown on CoCrFeMnNi HEA was reduced due to the chemical instability of Fe^{2+} [14]. Despite the knowledge accumulated so far, the effect of Fe addition on the corrosion behavior of CoCrNi MEA remains unknown in the current literature.

The present work aims to study the passive properties of the passive films on CoCrNi MEA and CoCrFeNi HEA in Na_2CO_3 / $NaHCO_3$ solution and its relationship with the corrosion behavior. The results can supply a reference for the potential application of the MEA and HEA in the $Na_2CO_3/NaHCO_3$ environment.

2. EXPERIMENTAL

2.1 Materials and solution

The equiatomic CoCrNi MEA and CoCrFeNi HEA were fabricated with raw metal materials of pure elements (purity above 99.99 wt.%) by arc melting at 1700° C in high-purity Ar atmosphere, subsequently cooled in a vacuum induction furnace to indoor temperature. The cast ingots were remelted several times to achieve a homogeneous composition. Both the two alloys consist of single phase FCC structure [15,16]. Rectangular specimens with a size of $10 \times 10 \times 3$ mm were machined from the MEA and

HEA ingots, then carefully packaged with epoxy resin, leaving an exposed area of 1 cm^2 for testing. The specimens were abraded by using SiC water sandpaper sequentially from 180 to 2000 grit and then polished with diamond paste of 0.5 µm. Subsequently, the samples were cleaned, and air-dried. In this paper, the solution of 0.4 M Na₂CO₃ + 1 M NaHCO₃ with pH of 9.3 as the simulated alkaline soil environment [17,18] was employed to explore the corrosion behavior of two alloys. All the tests were performed at 30 °C.

2.2 Electrochemical tests

The electrochemical measurements were conducted on a CHI660E electrochemical workstation with a conventional three-electrode cell system, including the reference electrode (RE, saturated calomel electrode), the counter electrode (CE, platinum plate), as well as the working electrode (WE, alloy specimens). Before the test, the two alloys were soaked in the solution for 1 h to achieve a passive state. Then, the open-circuit potential (OCP) was measured for 30 min. The potentiodynamic polarization was performed from -1 V to 1 V at a potential sweep rate of 1 mV/s. According to the potentiodynamic polarization curve (Fig.1), the potentiostatic polarization test was carried out for 2 h at passive potentials of 0.12 V_{SCE} and 0.72 V_{SCE} selected from primary and secondary passivation regions, during which the i-t curves were recorded to ensure that stable passive films were formed on alloy surfaces. Subsequently, the electrochemical impedance spectroscopy (EIS) test was performed at the OCP in a frequency range of 100 kHz ~ 10 mHz and the disturbance signal amplitude was 10 mV. The ZSimpWin software was utilized to fit and analyze the EIS spectra. The Mott-Schottky plots were obtained at a fixed frequency of 1kHz from -0.7 V_{SCE} to 0.6 V_{SCE} with 50 mV/step.

2.3 Morphology characterization of passive film

After the above potentiostatic polarization, the topography characteristics of the passive films grown on the MEA and HEA were observed by atomic force microscopy (PSLA XE-100E AFM) under the non-contact mode.

3. RESULTS

3.1 Potentiodynamic and potentiostatic polarization curves

Fig. 1 exhibits the potentiodynamic polarization curves of CoCrNi MEA and CoCrFeNi HEA measured in Na₂CO₃ / NaHCO₃ solution. It can be seen that these two alloys display similar passivation behaviors with primary and secondary passivation regions, and a similar phenomenon is observed in our previous study of CoCrFeMnNi HEA in this solution [14]. And the corrosion potentials of the two alloys are nearly equal, indicating that they have analogous corrosion tendency. In the anodic branch, the anodic current density maintains steady near -0.34 ~ 0.3 V, implying the primary passivation region, which is due to the formation of oxide films on the surface of the two alloys. As potential rises, a sharp increase

in current density is observed. The appearance of inflection point "a" in the curves may be associated to the transformation of the film structure and composition, after which the alloys enter a secondary passive state [19]. In the primary passivation region, the polarization curve of the MEA is located at the left of that of the HEA, thus the corresponding passive current density (i_{pl}) is smaller than that of the HEA. However, in the secondary passivation area, the situation is just the inverse, i.e., its passivation current density (i_{pll}) is greater, compared with the HEA. The i_p values of the two alloys are summarized in Table 1. It is well known that i_p characterizes the corrosion rate of the alloy under the passivated state, and the greater i_p means the faster the corrosion rate [20]. In summary, compared to CoCrFeNi HEA, the corrosion rate of CoCrNi MEA is slower in the primary passivation area but faster in the secondary passivation area. Meanwhile, the two HEAs have larger i_{pll} than i_{pl} . They exhibit opposite laws in different passivation zones, so this difference is further investigated in terms of formation process and property of the films.



Figure 1. Potentiodynamic polarization curves of CoCrNi MEA and CoCrFeNi HEA in Na₂CO₃ / NaHCO₃ solution.

Table 1. The ip values of CoCrNi MEA and CoCrFeNi HEA in Na₂CO₃ / NaHCO₃ solution.

Alloys	$i_{pI} (10^{-6} \mathrm{A} \cdot \mathrm{cm}^{-2})$	$i_{pII} (10^{-5} \text{ A} \cdot \text{cm}^{-2})$
CoCrNi	6.378	9.993
CoCrFeNi	9.076	2.801

Fig. 2 exhibits the current density-time transients of CoCrNi MEA and CoCrFeNi HEA with passive films formed at the passive potentials of $0.12 V_{SCE}$ and $0.72 V_{SCE}$ selected from different passive regions. The current density sharply reduces with time during the early stage of passivation, which is due to the faster nucleation and growth rate of the film in comparison with its dissolution rate [21]. With prolongation of time, the current density maintains a relatively steady status, which is the characteristic of the balance between the formation and dissolution of passive film, meaning a dense and unbreakable film grown on the sample surface [22]. The fitting results of the steady-state current density (i_{ss}) of the two alloys at different film formation potentials are displayed in Table 2. The current density can be

utilized to explain the difference in the film formation process of the two alloys. Combined with Fig. 2(a), at the film formation potential of $0.12 V_{SCE}$ (primary passivation), the i_{ss1} value of the MEA is much lower than that of the HEA, implying that a highly protective and compact passive film is produced on the MEA. Conversely, at $0.72 V_{SCE}$ (secondary passivation), the i_{ss2} value of the HEA is lower than that of the MEA, reflecting that the protective performance of passive film on the HEA is superior in the secondary passive region. Known from the data in Table 2 and Fig. 2, the i_{ss2} values of the two alloys are significantly larger than i_{ss1} , which suggests that the secondary passive film exhibits inferior anticorrosion property. The above phenomenon and law can be verified by the following EIS result.



Figure 2. Comparison of typical current-time transients of CoCrNi MEA and CoCrFeNi HEA at the film formation potential of 0.12 V_{SCE} (a) and 0.72 V_{SCE} (b) in Na₂CO₃ / NaHCO₃ solution.

Table 2. Steady-state current densities of CoCrNi MEA and CoCrFeNi HEA at the film formationpotential of 0.12 V_{SCE} and 0.72 V_{SCE} in Na₂CO₃ / NaHCO₃ solution.

Alloys	i_{ss1} ($\mu A \cdot cm^{-2}$)	i_{ss2} ($\mu A \cdot cm^{-2}$)
CoCrNi	0.09775	4.204
CoCrFeNi	0.2305	3.52

3.2 Electrochemical impedance spectroscopy analysis



Figure 3. EIS curves of the passive films on the MEA and HEA at the film formation potential of 0.12 V_{SCE}: (a) Nyquist plots; (b) Bode plots.



Figure 4. Equivalent circuit model used for EIS data fitting.



Figure 5. EIS curves of passive films on the MEA and HEA at the film formation potential of 0.72 V_{SCE} : (a) Nyquist plots; (b) Bode plots.

The electrical properties are considered to be the key to understanding the protective property of passive film against corrosion. The EIS measurement was adopted to characterize the properties of films grown on CoCrNi MEA and CoCrFeNi HEA. Figs. 3 and 5 display the EIS curves of the passive films covered on the MEA and HEA after potentiostatic polarization at 0.12 V_{SCE} and 0.72 V_{SCE} for 2 h, respectively. And the electrical equivalent circuit (EEC) in Fig. 4 was applied for fitting the EIS data [23].

The Nyquist plots of two alloys (Figs. 3(a) and 5(a)) exhibit similar impedance spectroscopy characteristics of unfinished capacitive arcs, demonstrating similar passive mechanisms. The arc diameter represents the passive film resistance [24,25]. The increase of the semicircular arc diameter implies the enhancement of the film stability. As displayed in Fig. 3(a), at the film formation potential of 0.12 V_{SCE}, the arc diameter in the Nyquist plot of the MEA is much larger than that of the HEA. Generally, the greater arc diameter means the better the corrosion resistance. Likewise, the MEA has the higher impedance module value of |Z| at the low-frequency range of the Bode diagram in Fig. 3 (b). The Bode plots of the MEA and HEA show a linear relation with a slope of nearly -1 in the middle-frequency region, and the maximum values of phase angle are close to 70-90°, which indicates that stable passive films are grown on the two alloys [26]. However, as shown in Fig. 5(a), at 0.72 V_{SCE}, the MEA possesses a smaller capacitance arc diameter and lower phase angle than those of the HEA, implying a difference in the protective ability of passive films. The above data also display that the capacitance ring diameters

of the films grown on the two alloys in the primary passivation region are larger than those in the secondary passivation area, indicating that the primary passive films on the two alloys have better corrosion resistance.

The corresponding EEC in Fig. 4 is commonly used to fit the impedance spectra of intact passive film covering on the metal substrate. In this model, where R_s represents the solution resistance, R_f is the resistance of passive film, and Q_f denotes the passive film capacitance [3]. Tables 3 and 4 list the fitted electrochemical parameters for EIS diagrams of the passive films. In Table 3, larger R_f and smaller Q_f suggest that the dense primary passive film on the MEA has higher protection in comparison with those of the HEA. On the contrary, after the second passivation, the R_f value of the HEA is larger than that of the MEA, and the Q_f value exhibits an opposite result, demonstrating that the secondary passive film on the HEA surface possesses a better protective performance. Additionally, the R_f values in Tables 3 and 4 demonstrate that the secondary passive film has inferior anti-corrosion performance.

Table 3. The fitted electrochemical parameters for EIS diagrams of the passive films formed on CoCrNiMEA and CoCrFeNi HEA at the film formation potential of 0.12 V_{SCE}.

Alloys	R_s ($\Omega \cdot cm^2$)	$\frac{R_{\rm f}}{(10^5 \Omega \cdot {\rm cm}^2)}$	$Q_{\rm f}$ (10 ⁻⁵ $\Omega^{-1} \cdot {\rm cm}^{-2} \cdot {\rm s}^{-n}$)
CoCrNi	7.453	10.16	2.078
CoCrFeNi	4.336	1.689	3.712

Table 4. The fitted electrochemical parameters for EIS diagrams of the passive films formed on CoCrNi MEA and CoCrFeNi HEA at the film formation potential of 0.72 V_{SCE}.

Alloys	R_s ($\Omega \cdot cm^2$)	$\frac{R_{\rm f}}{(10^5 \Omega \cdot \rm cm^2)}$	${Q_{\rm f} \over (10^{-5} \ \Omega^{-1} \cdot \ {\rm cm}^{-2} \cdot \ {\rm s}^{-n})}$
CoCrNi	6.924	0.9163	5.712
CoCrFeNi	4.342	0.9805	4.895

3.3 Mott-Schottky curve analysis

Numerous literature have shown that passive film on the alloy surface is highly correlated with the corrosion behavior of metals [27,28]. The Mott-Schottky curve was adopted to study the semiconducting properties of the passive films produced on the two alloys. The following formulas exhibit the relationship between the space charge capacitance (C) and the electrode potential (E):

$$\frac{1}{c^2} = +\frac{2}{eN_D\varepsilon\varepsilon_0} \left(E - E_{FB} - \frac{kT}{e} \right), \text{ for n-type semiconductor}$$
(1)
$$\frac{1}{c^2} = -\frac{2}{eN_A\varepsilon\varepsilon_0} \left(E - E_{FB} - \frac{kT}{e} \right), \text{ for p-type semiconductor}$$
(2)

where ε denotes the relative dielectric constant of the passive film (here is considered as 12 [29]), ε_0 is the vacuum permittivity constant (8.854×10⁻¹⁴ F·cm⁻¹), and e is the electron charge (1.602×10⁻¹⁹ C). N_A and N_D are the acceptor and donor densities (cm⁻³), respectively. E and E_{FB} represent the applied potential and the flat band potential. k is the Boltzmann constant $(1.38 \times 10^{-23} \text{ J} \cdot \text{K}^{-1})$ and T is the absolute temperature (K). N_A and N_D can be calculated from the slopes (m) of the linear segments within C⁻² versus E plots through formula 3.



Figure 6. Mott–Schottky plots (a), carrier densities (b) and thickness (c) of the passive films formed on the MEA and HEA at the film formation potential of 0.12 V_{SCE} in Na₂CO₃ / NaHCO₃ solution.

Figs. 6(a) and 7(a) present the Mott-Schottky curves of passive films produced on the MEA and HEA under potentiostatic polarization for 2 h at 0.12 V_{SCE} and 0.72 V_{SCE} . Two linear regions can be seen in all plots. The linear segments of positive and negative slopes mean different electronic structures of the films, which reflects that the passive films exhibit n/p-type semiconductor properties [30]. According to the point defect model, it is well known that the higher the carrier densities within the passive film, the worse the film stability and the more vulnerable it is to be attacked.

As exhibited in Fig. 6(b), the N_A and N_D values of the HEA are larger than those of the MEA, which suggests that the film grown on the HEA surface in primary passivation region possesses a higher defect density. Thus, combined with the higher R_f value, the primary passive film on the MEA is more complete and compact, compared with that of the HEA. In contrast, in Fig. 7(b), the N_A and N_D values of secondary passive film on the HEA are smaller than those of the MEA, which indicates that the protection performance of the film formed on the MEA surface is worse than that of the HEA. The thickness (d) of passive film can be obtained by formula 4, and the result is drawn in Figs. 6(c) and 7(c). Compared to the HEA, the thicker passive film on the MEA surface in primary passivation is beneficial for inhibiting the permeation of corrosive ions and reducing the corrosion of the matrix to a certain

degree. However, in secondary passivation, the MEA has a thinner passive film, and the law is inverse. In addition, for secondary passivation film, the higher carrier densities reveal that more amount of defects within the film decrease its protective ability.

(A)

$$d = \left[\frac{2\varepsilon\varepsilon_{0}}{eN_{D}}\left(E - E_{FB} - \frac{kT}{e}\right)\right]^{1/2}$$
(4)
$$\int_{0}^{\frac{3}{2}} \int_{0}^{\frac{3}{2}} \int_{0}^{\frac{3}{$$

Figure 7. Mott–Schottky plots (a), carrier densities (b) and thickness (c) of the passive films formed on the MEA and HEA at the film formation potential of 0.72 V_{SCE} in Na₂CO₃ / NaHCO₃ solution.

3.4 Topography characteristic of passive film

According to the above results, the structural difference of passivation films formed at $0.12 V_{SCE}$ and 0.72 V_{SCE} may affect the corrosion resistance of the two alloys to some extent. To intuitively explore the difference, an AFM measurement was adopted to observe the morphologies of surface films. Figs. 8 and 9 show the AFM topography morphologies of passive films on the MEA and HEA after potentiostatic polarization for 2 h at different potentials, and the height data of section profile along a straight line are exhibited. As shown in Fig. 8(a1-c1), CoCrNi MEA possesses compact, flat and intact passive film without obvious defects. However, in Fig. 8(a2-d2), there is a hole within the film formed on CoCrFeNi HEA surface. Thus, harmful ions and molecules easily penetrate the defective passive film, increasing the risk of pitting corrosion. Conversely, in Fig. 9(a1-d1), the secondary passive film of the MEA is uneven and defective, with a large height variation, compared with that of the HEA (Fig. 9(a2-c2)). Furthermore, in comparison with primary passive film (Fig. 8 (c1,d2)), the degree of heigh fluctuation depicted in Fig. 9(d1,c2) obviously increases. This characteristic is beneficial for the aggregation of solution ions, which accelerates the occurrence of corrosion. In Fig. 10, at 0.12 V_{SCE}, the

surface roughness (R_a) value of the HEA is greater than that of the MEA, while the opposite situation is presented for 0.72 V_{SCE}. Thus, the MEA displays good anti-corrosion performance compared with the HEA because of its compact and uniform primary passive film, while the secondary passivation films exhibit different protective effects.

In addition, according to our previous research [31], the difference in the composition of primary and secondary passive films is a key factor that affects their protective abilities. For the CoCrFeNi HEA, ferrous hydroxide or oxide generated at low potential [32] (primary passive region) decreases its corrosion resistance, and iron oxide or ferroferric oxide produced at high potential [33] (secondary passive region) promotes the protective performance due to the addition of Fe element, compared with the CoCrNi MEA.







Figure 8. Topography of the passive films formed on the MEA and HEA at 0.12 V_{SCE} in Na_2CO_3 / $NaHCO_3$ solution.





Figure 9. Topography of the passive films formed on the MEA and HEA at $0.72 V_{SCE}$ in Na_2CO_3 / $NaHCO_3$ solution.



Figure 10. Roughness of passive films formed on the MEA and HEA at 0.12 V_{SCE} and 0.72 V_{SCE}.

4. CONCLUSIONS

This study investigated the passive characterization of CoCrNi MEA and CoCrFeNi HEA in Na₂CO₃ / NaHCO₃ solution. The main conclusions were as follows:

The CoCrNi MEA and CoCrFeNi HEA exhibit secondary passivation characteristics in Na_2CO_3 / $NaHCO_3$ solution. In primary passivation region, a highly protective and dense passive film is grown on the MEA, which exhibits better corrosion resistance. While the protective performance of passive film grown on the HEA is superior in the secondary passive region. The secondary passive film on the two alloys has inferior anti-corrosion resistance, compared with that of primary passive film. The increase in potential is not conducive to the formation of a stable and thick passive film, which reduces the protection of the film.

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References

- 1. J.W. Yeh, S.K. Chen, J.Y. Gan, S.J. Lin, T.S. Chin, T.T. Shun, C.H. Tsau and S.Y. Chou, *Metall. Mater. Trans. A*, 35 (2004) 2533.
- 2. K. Lu, A. Chauhan, M. Walter, A.S. Tirunilai, M. Schneider, G. Laplanche, J. Freudenberger, A. Kauffmann, M. Heilmaier and J. Aktaa, *Scr. Mater.*, 194 (2021) No.113667.
- 3. H. Wang, P. Liu, X.H. Chen, Q.Q. Lu and H.L. Zhou, J. Alloy. Compd., 906 (2022)No.163947.
- 4. S. Chen, H.S. Oh, B. Gludovatz, J.K. Song, E.S. Park, Z. Zhang, R.O. Ritchie and Q. Yu, *Nat. Commun.*, 11 (2020) 826.
- 5. D.B. Miracle and O.N. Senkov, Acta Mater., 122 (2017) 448.
- Y.L. Zhao, T. Yang, Y. Tong, J. Wang, J.H. Luan, Z.B. Jiao, D. Chen, Y. Yang, A. Hu, C.T. Liu and J.J. Kai, *Acta Mater.*, 138 (2017) 72.

- D.H. Xiao, P.F. Zhou, W.Q. Wu, H.Y. Diao, M.C. Gao, M. Song and P.K. Liaw, *Mater. Des.*, 116 (2017) 438.
- 8. A. Panigrahi, T.S. Acharya, P. Sengupta, D. Kumar, L. Sarangi, N. Kumar, D. Debasish, S. Suwas, S. Basu and M. Debata, *Mater. Sci. Eng. A*, 832 (2022) No.142451.
- 9. O. Mohamed, M. Hassan, M. Egilmez, W. Abuzaid, T. Ibrahim and M. Khamis, *Mater. Today Commun.*, 30 (2022)No.103015.
- 10. J.L. Lv, Z.H. Tan and L. Tong, Intermetallics, 141 (2022) No.107423.
- 11. X.L. Shang, Z.J. Wang, F. He, J.C. Wang and J.J. Li, Sci. China Technol. Sc., 61 (2018) 189.
- 12. R.F. Zhao, B. Ren, B. Cai, Z.X. Liu, G.P. Zhang and J.J. Zhang, *Results Phys.*, 15(2019)No. 102667.
- 13. L. Coutu, L. Chaput and T. Waeckerle, J. Magn. Magn. Mater., 215-216 (2000) 237.
- 14. M. Zhu, B.Z. Zhao, Y.F. Yuan, S.M. Yin, S.Y. Guo and G.Y. Wei, *Mater. Chem. Phys.*, 279 (2022) No.125725.
- 15. M. Zhu, F. He, Y.F. Yuan, S.Y. Guo and G.Y. Wei, Intermetallics, 139 (2021) No. 107370.
- 16. D.P. Wang, J.W. Shen, Z. Chen, F.G. Chen, P.Y. Guo, Y.X. Geng and Y.X. Wang, *Acta Metall. Sin.* (Engl. Lett.), 34 (2021) 1574.
- 17. M. Zhu, B.Z. Zhao, Y.F. Yuan, S.Y. Guo and G.Y. Wei, *J. Electroanal. Chem.*, 882 (2021) No.115026.
- 18. A.Q. Fu and Y.F. Cheng, Corros. Sci., 52 (2010) 2511.
- M.J. Muñoz-Portero, J. García-Antón, J.L. Guiñón and V. Pérez-Herranz, Corros. Sci., 51 (2009) 807.
- 20. J.Z. Lu, X. Xu, H.F. Lu, Y. Su, M.X. Peng, F. Xing and K.Y. Luo, *Corros. Sci.*, 195 (2021) No.109976.
- 21. N. Ebrahimi, M.H. Moayed and A. Davoodi, Corros. Sci., 53 (2011) 1278.
- 22. Y.X. Qiao, Y.G. Zheng, P.C. Okafor and W. Ke, *Electrochim. Acta*, 54 (2009) 2298.
- 23. H. Luo, H.Z. Su, C.F. Dong and X.G. Li, Appl. Surf. Sci., 400 (2017) 38.
- 24. H. Luo, S.J. Gao, C.F. Dong and X.G. Li, *Electrochim. Acta*, 135 (2014) 412.
- 25. A.A. Hermas and M.S. Morad, Corros. Sci., 50 (2008) 2710.
- 26. M. Ray and V.B. Singh, J. Electrochem. Soc., 158 (2011) 359.
- 27. A.D. Paola, Electrochem. Acta, 34 (1989) 203.
- 28. K. Oh, I.-u.-H Toor, S. Ahn and H. Kwon, *Electrochim. Acta*, 88 (2013) 170.
- 29. L. Wei, Y. Liu, Q. Li and Y.F. Cheng, Corros. Sci., 146 (2019) 44.
- 30. D.D. Macdonald, J. Electrochem. Soc., 139 (1992) 3434.
- 31. M. Zhu, Q. Zhang, B.Z. Zhao, Y.F. Yuan and S.Y. Guo, J. Mater. Eng. Perform., 30 (2021) 918.
- 32. D.H. Davies and G.T. Burstein, Corrosion, 36 (1980) 416.
- 33. A.Q. Fu and Y.F. Cheng, Corros. Sci., 52 (2010) 612.

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