Formation of Fe-Sn intermetallic layer and its effect on the corrosion of 304 stainless steel in high temperature water

Jian-jun Guan¹, Hong-yuan Zhong¹, Li Feng², Yan Zhao^{1*}, Feng Liu¹, Ping Liang¹, Cong-qian Cheng³, Jie Zhao³

¹ School of Mechanical Engineering, Liaoning Shihua University, Fushun 113001, Liaoning, China
 ² School of Electrical Engineering, Shengyang Polytechnic College, Shenyang 110045, China
 ³ School of Materials Science and Engineering, Dalian University of Technology, Dalian 116085, Liaoning, China
 *E-mail: zhaoyan-a@163.com

Received: 2 December 2018 / Accepted: 6 February 2019 / Published: 10 March 2019

Fe-Sn compound layer on interface was studied during the interaction between liquid Sn and 304 stainless steel (304 SS), and the effect of the intermetallics on the corrosion of 304 SS in 300 °C high temperature water was researched. The experimental results indicate that a (Fe, Cr)Sn₂ compound layer forms at the Sn/304 SS interface. The average thickness of the layer is in proportion to square root of reaction time, indicating a diffusion control process for the intermetallics growth. After corrosion in 300 °C water, the (Fe, Cr)Sn₂ layer changes surface oxide film composition from hematite Fe₂O₃ and spinel Fe₃O₄ to SnO₂ and spinel Fe₃O₄. Microcracks and spallation tendency in the oxide films is due to the Fe-Sn intermetallics attachment. From the potentiodynamic polarization, the oxide film that formed on stainless steel with Fe-Sn intermetallics attachment significantly deteriorated the corrosion resistance compared with that the samples without intermetallics attachment.

Keywords: Sn, Stainless steel; Intermetallics, liquid-solid reactions, Oxidation, High temperature water

1. INTRODUCTION

It is important to comprehend the compatibility of solid metals with low melting point metals for facility safe in electronic industry and nuclear plant [1-3]. Specially, according to international standards, the contact with low melting point metal should be avoided during stainless steel manufacturing. If the contact is unavoidable, liquid metal embrittlement and corrosion will be occur under high temperature service circumstance [4-6]. Low melting point metal Sn is used as locating die in the manufacturing. Sn can accelerate material corrosion and cause brittle fracture in the manufacturing [7, 8]. The interaction between Sn and 304 SS and its influence on the property of stainless steel become a critical issue. It was

reported that the formation of interfacial intermetallic compounds is crucial to the interaction mechanism between liquid Sn and solid metals. The phase structure of Fe-Sn intermetallic was studied, and the diffusion phenomena in Fe-Sn system was reported [9, 10]. It is reported that the reaction of Sn with stainless steel may produce Fe-Sn compound [11-16]. The Fe-Sn compound layer is hard to be thoroughly diminished due to the intrinsic high corrosion resistance. Actually, a large amount of Fe-Sn compound still remain even the surface Sn was dissolved by acid cleaning. Microstructure and growth behavior of Fe-Sn intermetallics have been discussed by extensive reports. However, the formation of Fe-Sn compound between liquid Sn and stainless has not yet been systematically studied.

Normally, stainless steels are already worked in high temperature water in nuclear plant and chemical industry. The the oxide film nature affect the degradation and local corrosion resistance of stainless steel [17, 18]. The surface quality of stainless steel in manufacturing is important in determining corrosion and oxidation properties [19]. In the process of stainless steel manufacturing and application, surface related problems is proposed, such as surface pretreatment and surface contamination. Warzee et al [20] studied the corrosion of stainless steel that was preliminary treated in high temperature water, but failed to identify the dissimilarities on the surface treatments. Moreover, the effect of grinding, electropolishing and cold forming on the oxidation behaviour of stainless steel has been studied [21-24]. No previous studies have been conducted on the effect of surface contamination on the corrosion of stainless steel in high temperature water. To date, less work focuses on establishing a direct correlation between oxide films in high temperature water and surface contamination of stainless steel. Since a large amount of residual Fe-Sn compound still remain even after long time acid cleaning, the role of the remained Fe-Sn compounds on the corrosion behaviour of stainless steel has been our focus.

In the work, the formation of interfacial Fe-Sn compound was investigated by characterizing the thickness and morphology of compound layer based on the reaction of liquid Sn with 304 SS. The effect of the remained Fe-Sn compound on the corrosion process of 304 SS in 300 °C water was investigated by examining the morphological characteristics, phase structure and electrochemical properties of oxide films.

2. EXPERIMENTAL

2.1 Sample preparing

AISI 304 SS is used, and its chemical composition was shown in Table 1. The samples were mechanically ground to $1200^{\#}$ emery paper and reacted with liquid Sn immediately after grinding. The reaction time is planned as 10 min, 60 min and 240 min at 250 °C.

С	Cr	Ni	Mn	Si	S	Р	Fe
0.025	17.96	9.21	1.06	0.64	0.005	0.02	Bal.

 Table 1. Chemical composition of the 304 SS (wt.%)

The high temperature and high pressure water corrosion test was implemented in a 1 L autoclave, and the medium solution was deionized water. The temperature control instrument is precisely controlled by a program. The experimental temperature is 300 ± 5 °C, the pressure is 15 ± 2 MPa, and the corrosion time is 24 h, 120 h, 240 h, 360 h and 480 h. The surface Fe-Sn compound can not be melted in such high temperature water for the melting point of Fe-Sn compound is 513 °C [9]. For comparison, samples without Fe-Sn compound attachment were also prepared.

2.2 Microstructure and phase composition examination

After the interaction between Sn and 304 SS, the samples were etched with a solution containing 93 vol.% ethanol, 5 vol.% nitric acid, and 2 vol.% hydrochloric acid after they were inlaid with resin and polished. To expose the Fe-Sn compound layer, surface attached Sn was dissolved by a solution including 90 vol.% ethanol, 10 vol.% nitric acid. The cross section morphology and surface morphology were observed by JSM5600-LV and Zeiss Supra 55 scanning electron microscope (SEM). The element composition of the intermetallics was tested by OXFORD energy X-ray spectroscopy (EDS).

To characterize the degree of interaction between the Sn and 304 SS, the thickness of the compound was measured using Imagepro-Plus image analysis software, in which the thickness of the interfacial compound was measured by analyzing cross section morphology map. Each sample was measured 3 to 5 times to ensure the accuracy of the experimental results.

The interfacial compound phase components were tested by X-ray diffraction (XRD). The instrument model used is SHIMADZU XRD-6000. The Cu target K α ray was selected, and the scanning speed was 2θ /min, and the step length was 0.02° .

The samples were corroded in high temperature water. The morphology of corrosion products was examined by SEM. The traditional X-ray diffraction can not distinctively indentify the phase structure of thin oxide film. So synchrotron radiation-grazing incidence X-ray diffraction (SR-GIXRD) was conducted. SR-GIXRD was carried out at the 1W1A scattering station on the 1W1 beam-line of the Beijing Synchrotron Radiation Facility (BSRF) is conducted. The wavelength λ was 0.154 nm and the grazing incidence angle was 0.3°, respectively. Traditional X-ray diffraction (XRD-6000) is used for comparison.

2.3 Electrochemical analysis

In the current study, the measurements such as cross section SEM observation of oxide film were not used to characterize the thin oxide film due to the low accuracy. Generally, the variation in composition and structure of surface oxide films can affect the electrochemical behavior of samples. Therefore, potentiodynamic polarization was adopted to characterize the oxide layers. The samples were electrochemically tested using a CS350 electrochemical workstation. The sample was tested in a three-electrode system with 3.5% NaCl solution. The saturated calomel electrode (SCE) was the reference electrode, the platinum electrode was the auxiliary electrode, and the sample was the working electrode.

The effective area was 0.942 cm^2 . Potentiodynamic polarization curve was obtained by scanning between -0.7 to 1.0 V (SCE) at a scanning rate of 1 mV/s.

3. RESULTS AND DISCUSSION

3.1 Formation of Fe-Sn intermetallic layer

It is showed in Fig. 1 that the cross section morphologies of interface layer formed by interaction between Sn and stainless steel. A thick Sn layer attached to the stainless steel after 10 min of reaction is shown in Fig. 1(a). A very thin and discontinues Fe-Sn intermetallic compound (IMC) layer forms at the rough interface between the Sn and stainless steel. The Fe-Sn IMC layer grows with increasing reaction time. After 60 min of reaction, in Fig. 1(b), Sn adheres to the stainless steel surface to form a block or strip compound. In Fig. 1(c), the interface becomes regular and the composition of Fe-Sn IMC layer is 70 at.% Sn, 4 at.% Cr, and 26 at.% Fe measured by EDS, which is close to the stoichiometry of FeSn₂ intermetallic compound.



Figure 1. Cross section micrographs after liquid Sn reacted with 304 SS at 250 °C for different time: (a) 10 min, (b) 60 min, (c) 240 min.

The formation of FeSn₂ compound layer during the reaction between liquid Sn and Fe was observed by van Beek et al. [10] and Kajahara et al. [15]. The FeSn₂ layer with a columnar microstructure was observed after 1 h of reaction due to the fast growth in the previous studies [15]. In this experiment, the solid substrate is stainless steel and the reaction temperature is 250 °C ,which is lower than that described by Kajahara et al [15]. Thus the dissimilar in the initial and boundary conditions between the reactions in this study and in the study of Kajahara et al is attributed to form microstructure of the intermetallic layer. Indeed, only thin layer of FeSn₂ particles was observed by Dariavach et al [12] and Ye et al [14] on the reaction of FeNi alloy with Sn below 300 °C.

It is showed in Fig. 2 that the SEM surface morphology of the intermetallic layer. The intermetallic layer is composed of many tiny grains after 10 min of reaction (Fig. 2a). Stick-type grains were realized by 60 min of reaction (Fig. 2b). The grains coarsen with the increasing reaction time and gradually grow into plate-type and block-type grains after long time reaction (Fig. 2c). XRD pattern of the intermetallics is shown in Fig. 3. XRD pattern reveal that the intermetallic layer is FeSn₂ crystal. From EDX result, the intermetallics contains Cr element, which indicated that small amount of Fe atoms

in FeSn₂ were substituted by Cr atoms.



Figure 2. Surface morphology of Fe-Sn intermetallics layer after liquid Sn reacted with 304 SS at 250 °C for different time: (a) 10 min, (b) 60 min, (c) 240 min



Figure 3. XRD pattern of Fe-Sn intermetallics after 240 min of reaction

The growth kinetics of intermetallic interface can be described by the following equation:

$$L = kt^n \tag{1}$$

where *L* is the interface thickness, *k* is the growth coefficient, *n* is the time exponent, and *t* is the reaction time. The intermetallic growth is controlled by diffusion when the time exponent *n* is nearly equal to 1/2. While, an interface reaction process is responsible for the intermetallics growth if the *n* value is evaluated as 1 [14]. From Eq. (1), the relationship between FeSn₂ thickness and reaction time is showed in a log-log plot, and *n* is evaluated as 0.523,which indicated that a more perfect relationship between *L* and $t^{1/2}$ has been obtained.

Fig. 4 shows the thickness and average diameter of FeSn₂ grains calculated from the cross section micrographs and morphologies of FeSn₂ layers. The linear relationship between average diameter and $t^{1/2}$ indicates that the coarsen of FeSn₂ grains during the diffusion process. Many researchers have reported the growth kinetics of FeSn₂ layer during the liquid-solid interfacial reactions [11-15]. Most of the kinetics curves reported reveal a diffusion controlled growth of FeSn₂ layer. The growth coefficients of FeSn₂ layer is at a range of 0.008~0.18 μ m/s^{1/2}. The growth coefficient for Sn/304 SS at this work is higher than that for SnCu/Fe and SnPb/Fe couples, which is probably due to the oxide film that is produced on the Fe substrate quickly before interaction [25, 26].



Figure 4. Thickness of Fe-Sn intermetallics layer and average size of Fe-Sn intermetallics grains during the reaction of Sn with 304 SS at 250 °C

 Table 2. Growth coefficients of FeSn₂ layers at different conditions in various liquid/solid couples [11-15]

	Reaction temperature (°C)	Fe-Sn compound	Growth coefficient (μ m/s ^{1/2})
SnCu/Fe [11]	250	FeSn ₂	0.0132
SnPb/Fe [11]	250	FeSn ₂	0.0080
SnAgCu/Fe42Ni [12]	260	(Fe, Ni)Sn ₂	0.0177
Sn/FeNiP [13]	270	FeSn ₂	0.021
Sn/Fe42Ni [14]	270	FeSn ₂	0.175
Sn/Fe [15]	430	FeSn ₂	0.173
Sn/304 SS (this work)	250	(Fe, Cr)Sn ₂	0.0697

3.2 Morphology and phase characteristic of oxide film after oxidation

Fig. 5 shows SEM morphologies of the oxide films on 304 SS exposed in high temperature water. Without surface FeSn₂ layer, the oxide film is composed of faceted particles and irregular tiny ones. The faceted particles are loosely grown on the surface while the tiny ones are closely packed, as shown in Fig. 5(a). The oxide particle size increases with increasing oxidation time, and some of the faceted particles grow into irregular sized ones (Fig. 5c and e). For the FeSn₂ coated samples, the surface is comprised of small loose and micrometer-sized faceted particles. Micro cracks form on the surface (Fig. 5b). As exposure period increases up to 240 and 480 h, polyhedral bulk oxides are more abundant, aggregate on fine powdered oxides. It is drawn from the EDS analysis of selected regions in Fig. 5(d) that the faceted particles consist of Fe-rich oxide, and that the small loose particles are Sn-rich oxides, as shown in Table 3.



Figure 5. SEM morphologies of the oxide films produced on 304 SS after oxidation in 300 °C water for different time: (a) without FeSn₂, 24 h (b) with FeSn₂ adherence, 24 h (c) without FeSn₂, 240 h (d) with FeSn₂ adherence, 240 h (e) without FeSn₂, 480 h (f) with FeSn₂ adherence, 480 h

Table 3. Chemical composition at the selected regions (shown in Fig. 5(d), wt.%)

	0	Fe	Cr	Ni	Sn
Area A	32.1	5.3	0.7	0.8	61.1
Particle B	31.3	60.9	0.7	4.2	2.9

Fig. 6 shows the average size of faceted and tiny irregular oxides. For the samples without FeSn₂

layer, the average size of faceted and tiny irregular particles increases with increasing oxidation time. However, the average size is below 0.5 μ m. In the case of FeSn₂ attached samples, the size of faceted particles can grow up to 2 μ m, although much stronger fluctuation of particle size was evidenced.



Figure 6. Average size of oxide particles on 304 SS after oxidation in 300 °C water

The XRD patterns of the oxide films on the stainless steel exposed to 300 °C water is showed in Fig. 7. The phase type of oxides cannot be clearly identified from the conventional XRD patterns (Fig. 7a). The patterns also include the diffraction peaks of γ phase and α phase in stainless steel. The presence of α phase is mainly attributed to the deformation layer that formed during the grinding process with sandpaper [21]. In Fig. 7(b), the corrosion product consists of SnO₂, (Fe, Cr)₃O₄ and (Fe, Cr)₂O₃ on FeSn₂ attached stainless steel by conventional XRD examination.



Figure 7. XRD patterns of the oxide films on 304 SS with exposure of 24 and 480 h in 300 °C water: (a) without FeSn₂ adherence, (b) with FeSn₂ adherence

The SR-GIXRD patterns of the oxide films are shown in Fig. 8. In Fig. 8(a), the characteristic peaks of oxide film on the sample without Fe-Sn intermetallics adherence are located between the Fe₂O₃ and Cr₂O₃ peaks after 24 h of exposure. The analysis of EDS composition indicates that the oxide films contain Cr element. The oxide in high temperature water for 24 h forms as (Fe, Cr)₂O₃ [17, 18]. For 480 h exposure, the intensities of hematite (Fe, Cr)₂O₃ peaks decrease, whereas that of spinel (Fe, Cr)₃O₄ peaks increase, indicating a promotion in amount of spinel particles. In Fig. 8(b), the significant difference of the Fe-Sn intermetallics attached samples is that the oxide changes from hematite Fe₂O₃ to

 SnO_2 and spinel (Fe, Cr)₃O₄. Spinel particles is primarily composed of faceted type particles, and hematite type particles are mostly equiaxial grains with curving edges and blunt angles [17, 18, 27]. As evidenced by EDS, the faceted particles are oxide containing Fe, Cr and O elements. It is therefore considered that the larger faceted particles in Fig. 5 are spinel (Fe, Cr)₃O₄, while the smaller loose ones are SnO₂-based oxides. The high intensities of the characteristic peaks of spinel indicate that the faceted particles grow and highly crystallize in exposure of 480 h. There is no notable change in the SnO₂ peaks.



Figure 8. SR-GIXRD analysis of the oxide films on 304 SS for exposure of 24 and 480 h to 300 °C water: (a) without FeSn₂ adherence, (b) with FeSn₂ adherence

3.3 Effect of Fe-Sn intermetallics adhesion on corrosion properties of stainless steel

The macro morphologies of oxide films on stainless steel with Fe-Sn intermetallics adherence after 24 h and 240 h exposure is shown in Fig. 9. Sn-rich oxides cover the sample surface predominantly. Pits and micro cracks are also observed. A careful observation of location A in Fig. 9(b) is shown in Fig. 10. It reveals that the oxides in the pits are primarily composed of faceted particles. The micro cracks and pit formation illustrate the spallation tendency of oxide film. The existence of cracks and the loose Sn-rich particles indicate the intrinsic low adhesion of oxide film.



Figure 9. Macro morphologies and selected magnification of oxide film on stainless steel with FeSn₂ adherence, (a) 24 h oxidation, (b) 240 h oxidation



Figure 10. Micro morphologies of oxide film on stainless steel exposed in 300 °C water for 240 h, (a) with FeSn₂ adherence, (b) without FeSn₂ adherence

The experimental results show that the oxide film have been changed from Fe_2O_3 and Fe_3O_4 to SnO_2 and Fe_3O_4 due to the $FeSn_2$ layer adherence. The phenomena above can be attributed to the preferential oxidation of $FeSn_2$. It can be drawn from Pourbaix diagram for high temperature water [28, 29] that hematite type Fe_2O_3 is a stable phase on a clean surface of stainless steel at high corrosion potential region while spinel type Fe_3O_4 becomes stable at relative low potential region. The content of dissolved oxygen in high temperature greatly effects on the formation of oxide. High content of dissolved oxygen generally increases the corrosion potential and promote thermodynamic stability of Fe_2O_3 . The low dissolved oxygen in water is correspondent to low corrosion potential of stainless steel and prefers the formation of Fe_3O_4 oxide [30]. Since no deoxidization has been conducted in the current experiment, the high dissolved oxygen in the water is believed to responsible for the formation of hematite Fe_2O_3 after 24 h of oxidation (Fig. 8a). The hematite Fe_2O_3 is firstly formed and spinel Fe_3O_4 is produced subsequently ,which was also confirmed by Wu et al [18]. The experimental results on the samples without FeSn₂ are accordance with those of previous studies [18, 30].

According to the Fe-Sn phase diagram, melting point of FeSn₂ phase is approximately 513 °C. The existence of SnO₂ and absence of Fe₂O₃ oxide indicate a preferential oxidation of the FeSn₂ phase. On the basis of thermodynamic stability and experimental result, two reasons are possibly responsible to the absence of hematite for the samples subjected to FeSn₂ attachment. One of the reasons is that a large amount of dissolved oxygen at liquid/oxide interface has been consumed during the oxidation of FeSn₂ compound, and the amount of oxygen remained is decreased so that spinel oxides become thermodynamically stable. The other is that the huge difference in the chromium content available on the surface. While on a non-coated surface about 18 wt.% Cr are available to form corundum type structures, only 0.7 wt.% Cr can be found on the intermetallic surface as indicated by EDS in Table 2. It can be assumed that chromium diffusion through the thick intermetallic scale is rather slow compared to stainless steel without intermetallics adherence.

3.4 Electrochemical characterization of oxide film after corrosion

The oxide film quality was evaluated by electrochemical measurements in solution with 3.5 % NaCl. The potentiodynamic polarization curves of the samples is described as shown in Fig. 11. The

passive characterization is observed in all the polarization curves. For stainless steel substrate, the oxide film can improve the corrosion resistance by decreasing the passive current density. It is observed that oxidation time has no strong effects on the corrosion potentials and trans-passivation potentials. But it can cause the passive current densities decrease. The corrosion potential of stainless steel with FeSn₂ adherence is lower than that of without FeSn₂ sample. But the passive current density is much higher. It indicates that corrosion resistance is deteriorated because of FeSn₂ adherence. The presence of FeSn₂ could deteriorate the electrochemical properties of oxide films in high temperature water. In the previous study [26], the value of resistance derived from electrochemical impedance spectra (EIS) reveals the oxide porosity and the layer protectiveness at the oxide/solution/substrate interface. The quality of oxide film formed on stainless steel has been deteriorated due to the Fe-Sn intermetallics adhesion.



Figure 11. Potentiodynamic polarization curves measured in 3.5 % NaCl solution for 304 SS with and without FeSn₂ adherence after corrosion in 300 °C water for 0 h, 24 h and 480 h

4. CONCLUSION

(1) The interaction of liquid Sn with 304 SS produces the interfacial $FeSn_2$ layer containing a small amount of Cr. The layer thickness exhibits linear relationship with square root of reaction time, suggesting a diffusion controlled mechanism.

(2) After corrosion in 300 °C water, the surface oxide film is predominantly composed of faceted spinel (Fe, Cr)₃O₄ and SnO₂ for the Fe-Sn intermetallics attached samples. The average size of the faceted particles increases with prolonged oxidation time, but the morphologies do not vary during such oxidation. This result significantly differ from those without intermetallics adherence, where the small hematite (Fe, Cr)₂O₃ and spinel (Fe, Cr)₃O₄ are observed.

(3) Polarization tests result indicate that the oxide film of $(Fe, Cr)_3O_4$ and SnO_2 formed on intermetallics attached samples provides low corrosion protection. The degradation in corrosion resistance of stainless steel in high temperature water is possibly attributed to the low content of Cr in Fe-Sn compound and the formation of loose spallation spinel and SnO_2 films on the Fe-Sn intermetallics attached steel.

ACKNOWLEDEGMENT

This work was supported by by National Nature Science Foundation of China (NSFC No. 51571051), Science and Technology Research Fund of Liaoning Provincial Department of Education (L2017LQN026) and Scientific Research Cultivation Fund of Liaoning Shihua University (No.2016PY-024). The authors wish to thank all the staff members of the 1W1A beam line of Beijing Synchrotron Radiation Facility.

References

- 1. Y.H. Lu, Q.J. Peng, T. Shoji, J. Nucl. Mater., 347 (2005) 52.
- 2. S.K. Lin, R.B. Chang, S.W. Chen, M.Y. Tsai, C.M. Hsu, Mater. Chem. Phys, 154 (2015) 60.
- 3. Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components for Nuclear Power Plants, ASME NQA-1-2004, American Society of Mechanical Engineers, 2004.
- 4. J. Luo, H. Cheng, K.M. Asl, Y.C.J. Kiel, M.P. Harmer, Science, 1730 (2011) 333.
- 5. K.M. Asl, J. Luo, Acta Mater., 60 (2012) 149.
- 6. T. Auger, Z. Hamouche, L. Medina-Almazan, D. Gorse, J. Nucl. Mater., 377 (2008) 253.
- 7. H.S. Wang, K.D. Hsu, M.H. Wu, Y.Z. Su, Mater. Trans., 53 (2012)1148.
- 8. A. Hojna, F.D. Gabriele, J. Klecka, J. Nucl. Mater., 472 (2016)163.
- 9. H. Giefers, M. Nico, J. Alloys Compd., 422 (2006) 132.
- 10. J.A. Van Beek, S.A. Stolk, F.J.J. Van Loo, Z. Metallkd., 7 (1982) 439.
- 11. Y.C. Huang, S.W. Chen, W. Gierlotka, C.H. Chang, J.C. Wu, J. Mater. Res., 22 (2007) 2924.
- 12. N. Dariavach, P. Callahan, J. Liang, R. Fournelle, J. Electron. Mater., 35 (2006) 1581.
- 13. H. Zhou, J.D. Guo, J.K. Shang, J. Electron. Mater., 41 (2012) 144.
- 14. Y.W. Yen, H.M. Hsiao, S.W. Lin, P.J. Huang, C. Lee, J. Electron. Mater. 41(2012) 3161.
- 15. M. Hida, M. Kajihara, Mater. Trans., 53 (2012) 1240.
- 16. Y. Zhao, C.Q. Cheng, Z.Y. Cao, J. Zhao, Mater. Charact., 77(2013) 1.
- 17. M.Y. Wang, T.H. Li, T.K. Yeh, J. Nucl. Sci. Technol., 90 (2016) 666.
- 18. W. Kuang, X.Q. Wu, E.H. Han, Corros. Sci., 52 (2010) 4081.
- 19. S.G. Acharyya, A. Khandelwal, V. Kain, A. Kumar, Samajdar, Mater. Charact., 72 (2012) 68.
- 20. M. Warzee, J. Hennaut, M. Maurice, C. Sonnen, J. Waty, J. Electrochem. Soc., 112 (1965) 670.
- 21. S. Ghosh, M.K. Kumar, V. Kain, Appl. Surf. Sci., 264 (2013) 312.
- 22. S. Cisse, L. Laffont, B. Tanguy, M.C. Lafont, E. Andrieu, Corros. Sci., 56 (2012) 209.
- 23. Y.L. Guo, E.H. Han, J.Q. Wang, Mater. Corros., 66 (2015) 670.
- 24. S. Lozano-Perez, K. Kruska, I. Iyengar, T. Terachi, T. Yamada, Corros. Sci., 56 (2012) 78.
- 25. C.E. Jordan, A.R. Marder, Metall. Mater. Trans. B, 29B (1998) 479.
- Y. Zhao, J.J. Guan, F. Liu, P. Liang, C. Q. Cheng, J. Zhao, *High Temp. Mater. Processes*, 37 (2018) 387.
- 27. W.J. Kuang, E.H. Han, X.Q. Wu, J.C. Rao, Corros. Sci., 52 (2010) 3654.
- 28. B. Beverskog, I. Puigdomenech, Corros. Sci., 38 (1996) 2121.
- 29. B. Beverskog, I. Puigdomenech, Corros. Sci., 39 (1997) 107.
- 30. Y. Soma, C. Kato, M. Yamamoto, J. Electrochem. Soc., 159 (2012) C334.

© 2019 The Authors. Published by ESG (<u>www.electrochemsci.org</u>). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).