Investigation of Corrosion Product Films on Steel Surfaces of Drilling Materials in a Wet Hydrogen Sulfide Environment

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To study the corrosion process and corrosion products of drill pipe materials in a wet hydrogen sulfide environment, a corrosion immersion test of drill pipe materials was carried out. The G105 ordinary drill pipe material and the 105ss sulfur-resistant drill pipe material were placed in the standard corrosion liquid with hydrogen sulfide gas, and the soaking time of corrosion was controlled. The composition of the corrosion products on the sample surface was analysed via EDS. The main phases of the corrosion products were determined by XRD. The results showed that the corrosion products of the two kinds of drill pipe materials were mainly FeS and iron oxides. The film thickness and surface morphology of the corrosion products were observed via scanning electron microscopy (SEM). As the corrosion time increased, the corrosion product film on the surface of the sample gradually thickened, and the corrosion product particles gradually became larger; the particles included loose amorphous corrosion products and regular geometry crystals. Meanwhile, the corrosion products became dense. Compared with the G105 drill pipe material, the number of corrosion products on the sample surface of 105ss corrosionresistant drill pipe material was lower, and the size of the product particles was obviously smaller. At the same time, the electrochemical properties of the corrosion product films were studied by an electrochemical workstation. The corrosion product film can provide a certain barrier to the direct contact between the corrosion medium and the material matrix, thus slowing the corrosion rate of the corrosion medium to the drill pipe material.

Keywords: drill pipe; H₂S; corrosion product; corrosion time

1. INTRODUCTION

Drill pipes are an important part of a drill string, which plays a very important role in oil and gas exploration and the drilling process. The corrosion failure of oil drilling and pipeline is a common problem for oil and gas production and transmission [1]. A drill pipe failure will lead to more serious problems. When the drill pipe is broken, it will cause great economic losses. With the further exploitation

of the global oil and gas resources, the drilling environment of the oil and gas wells is becoming increasingly complex, and the service conditions of the drill pipe are worse. H_2S is the most common corrosion medium in oil and gas production, and it has a strong corrosive effect on drilling tools and oil and gas pipelines. In humid environments, hydrogen sulfide is prone to dissociation to form H⁺, HS⁻, and S²⁻ [2]. The HS⁻ and S²⁻ adsorbs on the metal surface and ultimately forms iron sulfur compounds[3], reducing plastic materials and resulting in crack initiation, and ultimately forming sulfide corrosion cracking (SCC)[4,5]; H⁺ enters metal material by diffusion, which eventually results in hydrogen induced cracking (HIC)[6].

At present, there are many studies on the corrosion mechanism and corrosion products of pipeline steel in hydrogen sulfide environments, but the corrosion of drill pipe material in wet hydrogen sulfide environments and its product films have rarely been reported[7-9]. In the wet hydrogen sulfide environment, the corrosion product film is also an important factor affecting the corrosion rate of hydrogen sulfide[10,11]. In different corrosion conditions, hydrogen sulfide corrosion products on the substrate can play a protective role, or accelerate the corrosion of the matrix material. The role of the corrosion product film in the corrosion process is affected by the morphology, composition and thickness of the film[12-15]. In this experiment, the corrosion behaviour of the drill pipe material in different corrosion conditions in a wet hydrogen sulfide environment was studied. The thickness of corrosion products and the surface morphology were observed by scanning electron microscopy. The composition of the corrosion product film were also determined by XRD. At the same time, we studied the variation law of the electrochemical performance of the corrosion product film via an electrochemical workstation.

2. EXPERIMENT

2.1. Materials and methods

The material used in the experiment is the G105 drill pipe material and 105ss sulfur-resistant drill pipe material according to the API standard. The chemical composition of the drill pipe materials is shown in Table 1. The 105ss sulfur-resistant drill pipe contains nickel, chromium, molybdenum, a vanadium content higher than the G105 drill pipe, and a manganese content lower than the G105 material. The G105 drill pipe material is quenched (heated to 870°C, heat preservation 30 min) and treated with high temperature tempering (temperature of 680°C, heat preservation 60 min) so that its microstructure becomes tempered sorbite. At the same time, the 105ss sulfur-resistant drill pipe material is quenched (Temperature greater than 800°C, holding time is greater than 30 min) and tempered (Temperature greater than 600°C, holding time is greater than 30 min) at a high temperature, and the final material morphology is also tempered sorbite.

Material	С	Si	Mn	Cr	Mo	Ni	Al	Cu
G105	0.25	0.25	1.06	0.88	0.16	0.02	0.013	0.01
105ss	0.28	0.25	< 0.50	>1.0	>0.4	>0.05	>0.01	>0.04

 Table 1 Chemical composition of drill pipe materials (wt. %)

The corrosion behaviour of drill pipe materials in the wet H₂S environment was studied via a static immersion test. According to the provisions of the United States Association of Corrosion Engineers NACE standard TM0177-2005, the corrosion solution used in this study is a standard A solution. A standard A solution consists of sodium chloride with a mass percentage of 5% and acetic acid with a mass percentage of 0.5% being dissolved in distilled water with a mass percentage of 94.5%[16]. The experimental setup is shown in Figure 1. The sample was longitudinally sampled from the middle of the wall thickness of the drill pipe, and the sample size was 100 mm × 20 mm × 5 mm. The sample was gradually polished with 100#, 240#, 600#, 800# sandpaper, polished on a polishing machine, ultrasonically cleaned, and then placed in a container, as shown in Figure 2. Before the test, N₂ was introduced into the solution for 2 hours to remove the oxygen in the solution. Then, H₂S gas was continuously introduced during the test to bring the solution to a saturated state, and the pH was controlled between 2.6 and 2.8.

The two kinds of drill pipe material samples were placed in the standard A solution, and the controlling times for the saturated hydrogen sulfide gas were 8 days, 12 days, 16 days, 20 days, 24 days, and 28 days. After corrosion, the morphology and composition of the corrosion products film on two kinds of drill pipe materials were analysed via scanning electron microscopy (SEM), X ray diffraction (XRD) and energy dispersive spectroscopy (EDS). The corrosion law of the material was studied with the increase of corrosion time. However, the growth mechanism of corrosion product film was mainly studied. At the same time, the electrochemical properties of the corrosion products' film were studied via electrochemical workstation, and the influence mechanism of the corrosion products on the corrosion performance of drill pipe materials was analysed.



Figure 1. The experimental setup



Figure 2. Sample soaking diagram

3. RESULTS AND DISCUSSION

3.1 Thickness of corrosion product film

The section of the G105 corrosion sample is shown in Figure 3. The figure shows that when the corrosion time is 8 days, the corrosion product film is discontinuously distributed in the steel matrix surface, and there is a clear dividing line between the film and the substrate. Moreover, the corrosion product film is loose and thin. Over time, the corrosion product film becomes dense, but there is still a clear boundary between the film and the substrate. Diagrams (b) and (c) show that there are cracks in the corrosion products. Over time, the crack at the joint of the corrosion product film and matrix began to expand to the interior of the corrosion products, and the corrosion products of the drill pipe material close to the outside is still relatively loose.





Figure 3. Cross section morphology of corrosion product film of G105 drill pipe material under different corrosion times. (a) 8 days, (b) 12 days, (c) 16 days, (d) 20 days, (e) 24 days, (f) 28 days.



Figure 4. Cross section morphology of corrosion product film of 105ss drill pipe material under different corrosion time. (a) 8 days, (b) 12 days, (c) 16 days, (d) 20 days, (e) 24 days, (f) 28 days.

The cross-section morphology of corrosion product film of the 105ss sulfur-resistant drill pipe is shown in Figure 4. When the corrosion time is 8 days, the corrosion product film is thin and discontinuously distributed on the surface of the steel pipe. Moreover, there is a clear demarcation line between the film and substrate, as shown in diagram (a). As the corrosion time increases, the corrosion product film grows thicker and becomes denser. The corrosion of the corrosion product film of diagram (f) is obviously denser than in diagram (e). However, the crack at the interface between the corrosion product film and the drill pipe matrix began to extend to the interior of the corrosion product, so obvious cracks were observed inside the corrosion product film. Overall, the corrosion product film of the sulfur-resistant drill pipe is relatively loose and similar to that of the common drill pipe.



Figure 5. Thickness of corrosion products on the surface of drill pipe material sample.

With the increase in corrosion time, the thickness of corrosion product film on the surface of drill pipe material is shown in Figure 5. The figure shows that with the increase in corrosion time, the thickness of the corrosion product film on the surface of the sample increases gradually. The thickness of the corrosion product film of the G105 drill pipe material increased rapidly between 8 and 12 days, mainly because of the strong corrosion of hydrogen sulfide on the drill pipe and the rapid increase of the film. As the corrosion time increased from 12 to 20 days, the thickness of the corrosion product film [17,18]. When the corrosion time was longer than 24 days, the film of the product continued to thicken. Because of the thick film of the corrosion product, it has a barrier to the permeation of hydrogen atoms [19].

With the increase in corrosion time, the corrosion product film thickness of the two kinds of drill pipe materials increased gradually. In addition, according to Figure 5, the slope of the curve gradually decreased over time, that is, the corrosion rate of the sample subjected to hydrogen sulfide gradually decreased. Therefore, with the increase in immersion time, the corrosion product film plays a role in slowing down the corrosion of drill pipe material, and plays a role in protecting the steel matrix of the drill pipe.

3.2 Surface morphology of corrosion products

Figure 6 shows with the increase in corrosion time, the corrosion product particles gradually become larger, and gradually become denser. When the corrosion time of G105 drill pipe material in

wet hydrogen sulfide environment was 8 days, the corrosion product film is discontinuous in the drill pipe material surface.



Figure 6. Morphology of corrosion products of G105 drill pipe materials at different corrosion times. (a) 8 days, (b) 12 days, (c) 16 days, (d) 20 days, (e) 24 days, (f) 28 days.

The distribution of corrosion products is random, and the growth density is relatively small. In addition, we can see the bare drill pipe metal material. With the increase in the corrosion time, the density of the corrosion product film increased gradually. The corrosion product film was uniformly covered on the surface of the whole sample. At the same time, the corrosion product film played a certain role in the direct contact between the wet hydrogen sulfide corrosion medium and the drill rod material matrix, which slowed down the corrosion rate of hydrogen sulfide. After 12 days of corrosion, the corrosion product film are granules of the same size. However, there was a gap between the particles and the particle structure, and the surface of the particles was covered with a loose flocculent corrosion product. After 16 days of corrosion, the corrosion products became larger, and the surface of the substrate. With the

increase in corrosion time, the morphology of the corrosion product film on the substrate surface tended to be stable.



Figure7. Morphology of corrosion products of 105ss drill pipe materials in different corrosion time. (a) 8 days, (b) 12 days, (c) 16 days, (d) 20 days, (e) 24 days, (f) 28 days.

The morphology of the corrosion product film of the 105ss drill pipe material at different corrosion times is shown in Figure 7. The graph shows that the corrosion product film of 105ss drill pipe material is similar to that of the G105 drill pipe material with the change of corrosion time in the wet hydrogen sulfide environment. With the increase in corrosion time, the surface of 105SS drill pipe material became covered with a thick layer of corrosion products from loose amorphous material to the appearance of regular crystals. Then, the corrosion products became denser. However, at the same corrosion time, the number of corrosion products on the surface of the sulfur-resistant drill pipe was substantially less than that on the ordinary drill pipes, and the particle size of the corrosion products was smaller.

This result shows that the hydrogen sulfide corrosion resistance of the sulfur-resistant drill pipe is much higher than that of the ordinary drill pipe; this is because of the appropriate proportion of chemical components in the sulfur-resistant drill pipe[20]. First, the manganese content was reduced. Manganese can promote the segregation of harmful elements such as phosphorus and sulfur in the steel of the drill pipe to grain boundaries. The harmful elements of the segregated will interact with the hydrogen atoms, so that the grain boundary binding force decreases and the hydrogen sulfide corrosion is increased. Second, an increase in the molybdenum content can promote the passivation of steel in acid and improve the corrosion resistance of the material. At the same time, the molybdenum element can form the dispersed precipitates with the sulfur ions produced by hydrogen sulfide and the carbon elements in the steel. Molybdenum carbide is a strong hydrogen atom trap, so Mo not only reduced the content of sulfur in the solid solution but also greatly reduced the diffusible hydrogen enrichment content. Molybdenum is the most effective element for hydrogen sulfide corrosion resistance. The addition of vanadium in steel can also improve the tempering stability of drill steel, which is beneficial to improve the corrosion of hydrogen sulfide[21]. Therefore, the corrosion degree of the sulfur-resistant drill pipe is smaller than the common drill pipe in the wet hydrogen sulfide environment.





Figure 8. EDS test of the corrosion product film on the surface of the G105 drill pipe sample at different immersion times.

To determine the main components of the corrosion products on the drill pipe surface, an EDS analysis was carried out. The EDS test of the corrosion product film on the G105 drill pipe sample is

shown in Figure 8. The main element content of the corrosion product film of G105 drill pipe material is shown in Table 2.

The sample number	Immersio n time/day	С	Fe	S	Cr	Other elements
a	8	4.48	87.17	1.03	1.36	5.96
b	12	3.20	60.19	36.61	0	0
с	16	5.54	57.54	36.92	0	0
d	20	5.35	55.57	34.60	0	4.38
e	24	5.87	57.74	36.39	0	0
f	28	4.42	60.81	34.77	0	0

Table 2. Main elements of the corrosion product film of G105 drill pipe material (wt%)

Table 2 shows that the corrosion products mainly contain two elements, sulfur and iron, so the main products can be inferred as iron sulfur compounds[22]. There are numerous other elements in the spectrum, such as Mn, C, Cr, Ni from the drill pipe material matrix, and the Na element is mainly derived from the corrosion immersion solution.





Figure 9. The EDS test of corrosion product film on the surface of 105ss drill pipe sample under different immersion time.

Table 3. The main element of corrosion product film of 105ss drill pipe material (wt%)

The sample number	Immersion time/day	С	Fe	S	Cr	Other elements
а	8	3.31	88.22	0.90	1.39	6.19
b	12	2.72	61.96	35.32	0	0
с	16	7.36	59.96	35.68	0	0
d	20	7.05	64.31	5.16	6.61	16.86
e	24	4.33	61.12	36.78	0.78	2.99
f	28	4.42	60.81	34.77	0	0

Table 2 shows that with the extension of the corrosion immersion time, the sulfur content of the corrosion products on the surface of the sample increases gradually, but the increase rate decreases over time.

Figure 9 shows the EDS tests of the surface corrosion product film of the 105ss sulfur-resistant drill pipe sample. The main elemental content of the corrosion product film of the 105ss drill pipe material is shown in Table 3. Table 3 shows that when the corrosion time was short, the C, Mn, Cr and other matrix materials were observed in the surface energy spectrum. With the increase in corrosion time, the corrosion product film gradually thickened, the main component of the corrosion product film changed into sulfur and iron, which was composed of one or more iron sulfides. The corrosion rate slowed down when the corrosion medium was physically impeded. However, when the corrosion product film of the 105ss sulfur-resistant drill pipe. At the same time, the ratio of sulfur and iron was also close to 1:1.72, which is slightly different from the ordinary drill pipe. XRD phase analysis was carried out to analyse the difference between the two drill pipes in the corrosion product film in the wet hydrogen sulfide environment.



Figure 10. XRD phase analysis of corrosion product film:(a)G105;(b)105ss

The G105 samples and 105ss sulfur-resistant samples were selected for 24 days of immersion in the saturated H₂S solution; the corrosion product film on the surface of the samples were analysed by XRD, and the results are shown in Figure 10. Figure 10 shows that after the corrosion of the saturated hydrogen sulfide solution, the composition of the corrosion product film on the surface of the two kinds of drill pipe materials is very similar; the corrosion products are mainly FeS, Fe₃O₄ and Fe₂O₃, and the peak value of FeS was higher than that of the other two compounds. The corrosion product film of the G105 drill pipe and 105ss sulfur-resistant drill pipe showed few differences in the compound contents, and the FeS content was the highest. This is similar to the EDS analysis results, as both the composition of the corrosion product film is very close to the composition of Fe, and the S content is high. Therefore, the composition and content of the two kinds of pipe materials in the saturated hydrogen sulfide solution after the formation of the immersion corrosion film were basically the same, and FeS was the main corrosion product[23-25]. Fe₃O₄ and Fe₂O₃ were the oxidation products formed in the air after the corrosion of the samples[26].

By comparing the major elements and components of the corrosion products of the sulfurresistant drill pipe and common drill pipe, the major elements of the two corrosion products are similar; moreover, the change in rules of the major elements of corrosion products are also similar to the increase in corrosion time, thus indicating that corrosion product film has a certain impact on the hydrogen sulfide corrosion. This result is related to the physical hindrance of the corrosion product film on the surface hydrogen adsorption concentration and the hydrogen diffusion to the drill pipe steel matrix. In addition, the chromium rich area appeared on the corrosion product film of the sulfur-resistant drill pipe.

3.4 Electrochemical characteristics of corrosion product film

The effect of the corrosion product film formed in the hydrogen sulfide environment on the corrosion performance of drill pipe was tested. The polarization curves of the samples were measured by a Reference 600 electrochemical workstation of American GAMRY Company. The experiment used three electrode systems, where the platinum electrode was the auxiliary electrode and the saturated calomel electrode was the reference electrode; soaked samples worked as the working electrode. The medium used in the test is a mass fraction of the 3.5% sodium chloride aqueous solution, which is made up of distilled water and analytical pure sodium chloride. The Tafel polarization curve measured a

potential sweep range of -250 mV - +400 mV (vs Ecorr) with a scan rate of 0.667 mV/s. The polarization curves of the G105 drill pipe material samples and 105ss drill pipe materials samples at different corrosion times are shown in Figure 11.



Figure 11. Polarization curve of drill pipe material after different time of corrosion times. (a) 8 days, (b) 16 days, (c) 24 days.

Materials	Soaking time (d)	Corrosion potential (Ecorr/V)	Corrosion current density (A.cm ²)
	8	-0.899	3.643e-5
G105	16	-0.682	3.218e-4
	24	-0.805	1.477e-4
	8	-0.842	1.293e-5
105SS	16	-0.746	2.259e-4
	24	-0.787	9.278e-5

Table 4. Polarization parameters of two kinds of drill pipe materials at different soaking times

Figure 11 shows that the corrosion product film has an obvious influence on the anodic polarization of the electrochemical corrosion system. At the same time, there are different degrees of passivation in the anodic polarization curves of the samples of sulfur-resistant drill pipe and ordinary drill pipe samples, and the cathode variation law is approximately the same. The results show that the corrosion product film produced on the surface of the sample after soaking has a protective effect on the sample[27].

For the G105 drill pipe material, the corrosion potential increases first and then decreases with as immersion time elapses, which shows that the corrosion resistance of the G105 sample is decreased first and then increased over time. The change trend of the sample is mainly related to the structure and composition of the corrosion product film on the surface[28-29]. When the immersion time was close to 24 days, the corrosion current density of the sample was relatively small, thus indicating that the corrosion product film on the surface of the sample effectively prevented the occurrence of metal corrosion. Based on the previous analysis of the corrosion product film was dense. A passivation film with protective properties was formed on the surface of the sample, so the corrosion rate of the sample was relatively low, which showed a relatively strong corrosion resistance. Similarly, the corrosion potential of the 105ss sulfur-resistant drill pipe samples showed an initial increase and then decreased as the immersion time elapsed. This shows that the corrosion variation law of the 105ss sulfur-resistant drill pipe material. This change trend is also mainly related to the structure and composition of the G105 drill pipe material. This change trend is also

4. CONCLUSIONS

(1) The thickness of the corrosion product film of the two kinds of drill pipe materials increased as the corrosion time elapsed. In the early stage, the thickness of the film increased rapidly, mainly because of the strong corrosion of hydrogen sulfide on the drill pipe, corrosion which made the product film increase rapidly. As the corrosion time elapsed, the thickness of the corrosion product film increased slowly, indicating that the corrosion rate of hydrogen sulfide decreased gradually with the existence of a protective corrosion film. At the same corrosion time, the thickness of the corrosion product film of the 105ss sulfur-resistant drill pipe is much smaller than that of the G105 drill pipe.

(2) As the corrosion time elapsed, the corrosion product particles of G105 drill pipe samples gradually became larger and more compact than the loose surface products. The surface corrosion product of the 105ss drill pipe material ranged from loose amorphous corrosion products to crystals with regular geometry and became more compact. At the same corrosion time, the particle size of the corrosion products of 105SS sulfur-resistant drill pipe samples was smaller than that of the G105 drill pipe samples. Combined with the analysis of the base material element composition, it can be seen that the corrosion resistance of the sulfur-resistant drill pipe is better than that of the common drill pipe.

(3) The main components of the corrosion product film for the two kinds of drill pipe materials are sulfur and iron, and they mainly exist in the form of FeS. However, there is a chromium rich area on the surface of the corrosion product film of sulfur-resistant drill pipes.

(4) As the immersion time elapsed, the corrosion potential of the corrosion products on the surface of the two kinds of drill pipe samples increased first and then decreased. The changing trend of the sample is mainly related to the structure and composition of the corrosion product film. The denser the corrosion product film is, the smaller the corrosion potential, and the higher the corrosion resistance. However, overall, the corrosion product film was relatively loose, so it only slowed down the corrosion rate and could not inhibit the corrosion.

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References

- 1. T.Ramgopal, F. Gui, J. Hawk, M.Ziomekmoroz, Foot & Ankle International, 21(2011) 686.
- 2. M. Liu, J. Wang, W. Ke. Corrosion Engineering Science & Technology, 48(2013) 380.
- 3. Z. F. Yin, W. Z. Zhao, Z.Q. Bai, Y.R. Feng, W. J. Zhou, *Electrochimica Acta*, 53(2008) 3690
- 4. Y. Han, X. Zhao, Z. Bai, C.X. Yin, Procedia Materials Science, 3(2014)447
- 5. M Monnot, R. P. Nogueira, V. Roche, G. Berthome, E. Chauveau, R. Estevez, M. Mantel, *Applied Surface Science*, 394(2017)132.
- 6. J. Kittel, V Smanio, M Fregonese, L. Garnier, X. Lefebvre, Corrosion Science, 52(2010)1386.
- 7. P.P. Bai, S.Q. Zheng, H. Zhao, Y. Ding, J. Wu, C.F. Chen, *Corrosion Science*, 87(2014)397.
- 8. L. Zhang, H. X. Li, F. X.Shi, J. W. Yang, L. H. Hu, M. X. Lu, *International Journal of Minerals Metallurgy & Materials*, 24(2017)401.
- 9. M.J. Hernanndez Gayosso, N Nava, G. Zavala Olivares, 51(2016) 626.
- A. Cervantes Tobón, M. Díaz Cruz, J. L. González Velázquez, J. G. Godínez Salcedo, R. Macías Salinas. *Int. J. Electrochem. Sci.*, 9 (2014) 6781.
- 11. A. Cervantes Tobón, M. Díaz Cruz, M. A. Domínguez Aguilar, J. L. González Velázquez. *Int. J. Electrochem. Sci.*, 10 (2015) 2904.
- 12. C.S. Zhou, X.Y. Chen, Z. Wang, S.Q. Zheng, X. Li, L. Zhang, Corrosion Science, 89(2014)30.
- 13. S.Q. Zheng, C.S. Zhou, X.Y. Chen, L. Zhang, J.Y. Zheng, Y.Z. Zhao, *International Journal of Hydrogen Energy*, 39(2014)13919.
- 14. W. Zhao, Y. Zou, K. Matsuda, Z. Zou, Materials & Design, 99(2016)44.
- 15. S.Q. Zheng, L.W. Liu, C.S. Zhou, L.Q. Chen, C.F. Chen. Int. J. Electrochem. Sci., 8 (2013) 1434
- 16. NACE Standard TM0177-2005: Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H₂S Environments.
- 17. J.S. Lee, Y. Kitagawa, T. Nakanishi, Y. Hasegawa, K. Fushimi, *Electrochimica Acta*, 220(2016)304
- 18. Y.E. Mendili, A. Abdelouas, J.F. Bardeau, Rsc Advances, 3(2013)15148.
- 19. A Hernández-Espejel, M.A. Domínguez-Crespo, R. Cabrera-Sierra, C. Rodríguez-Meneses, E. M. Arce-Estrada, *Corrosion Science*, 52(2010)2258.
- 20. A. Cervantes Tobón, M. Díaz Cruz, J. L. González Velázquez, J. G. Godínez Salcedo. Int. J. Electrochem. Sci., 9 (2014) 2254.
- 21. A. Tomio, M. Sagara, T. Doi, H. Amaya, N. Otsuka, T. Kudo, Corrosion Science, 98(2015)391.
- 22. C.C. Silva, J.P.S.E. Machado, A.V.C. Sobral-Santiago, H. B. D. Sant'Ana, J. P. Farias, *Journal of Petroleum Science & Engineering*, 59(2007)219.
- 23. B.S. Huang, Z.Y. Jiang, Z, Advanced Materials Research, 152-153(2010)659.
- 24. L.H. Han, M. Liu, S.J. Luo, T. J. Lu, Process Safety and Environmental Protection, 124(2019)63.

- 25. B.S. Huang, H. Peng, X. Chen, C.L. Gong, J.C. Li, *Corrosion Engineering, Science and Technology*, 52(2017)453.
- 26. B.S. Huang, X. Chen, L.P. Huang, Materials Science Forum Trans Tech Publications. 2015.
- 27. L.P. Wan, Y.F. Meng, G. Li, H.Zhou, Advanced Materials Research, 415-417(2012)2292.
- 28. B.S. Huang, J. Ying, H. Zhang, G. Liu, Y. B. Chen, J. C. Li, *Transactions of the Indian Institute of Metals*, 71(2017)1.
- 29. D.Z. Zeng, G. Tian, J.Y.Hu, Z. Zhang, T.H. Shi, W.Y. Liu, Q. Lu, S.B. Feng, *Journal of Materials Engineering and Performance*, 23(2014)4072.
- 30. Y.L Zhou, J. Chen, Y. Xu, Z. Y. Liu, Journal of Materials Science & Technology, 29(2013)168.
- 31. P. Bai, S. Zheng, H. Zhao, Y. Ding, J. Wu, C. Chen, Corrosion Science, 87(2014)397.

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