

The Influence of Critical Flow Velocity on Corrosion of Stainless Steel

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Abstract In order to find out the effect of fluid flow velocity on electrochemical reaction, the electrochemical parameters of super 13Cr stainless steel in 3.5% NaCl aqueous solution were measured by a jet flow system at different flow velocities. The electrochemical characters such as open-circuit potential and polarization curve were monitored online using a three-electrode electrochemical system. The results show that the increase in wall shear stress caused by the high flow velocity leads to the rupture of passive films and the exposure of fresh metal in the corrosive media, which cause the increase in corrosion rate. Meanwhile, the corrosion rate shows a significant growth when the flow velocity is less than 0–10.0 m/s. But it gradually decreases after reaching a maximum value.

Keywords Jet flow experiment · Electrochemical monitoring · Flow-induced corrosion · Critical flow velocity

Introduction

Fluid-induced corrosion is defined as an effect of the metal surface damage caused by the electrochemical reaction between metal surface and corrosive media. It is usually influenced by the change in the mass transfer rate of reactants, surface roughness and temperature.

The effect of flow pattern on corrosion character has been investigated by Yabuki [1], Salama [2], Neville [3, 4], McLaury [5], Postlethwaite [6], Bozzini [7], Keating [8], Malka [9] from many research aspects. The main topic of their study was to find out the change in mass transfer in near-wall boundary layer. A new model was explored to predict the detail corrosion rate based on the local flow pattern. At high flow velocity, Yong et al. [10] pointed out that the increase in wall shear stress caused by the high flow velocity led to oxygen concentration diffusion layer thinning. Besides this, the oxygen quickly transferred to the metal surface and caused the flow corrosion rate to increase. Zhang et al. [11] of Calgary University reported that increasing the flow velocity and decreasing the erosion angle can lead to the increase in corrosion rate.

At the same time, some effective and simple methods are used to corrosion calculations. For example, in laminar and turbulent states, the Chinese Academy of Sciences [12, 13] studied corrosion of metals in 3.5% NaCl solutions by combining numerical calculations with experimental studies. In addition, the mathematical model of corrosion turbulent state and laminar flow state was established by using wall function and k-epsilon two equation. These researches were mainly numerical and mathematical models, while experimental studies were relatively few. In the liquid/solid two-phase flow loop test, Shadley [14] of Tulsa University also studied the influence of flow rate on the corrosion rate in two-phase solution at high temperature and high pressure. It was found that the corrosion rate showed a lower–higher–lower trend with the change of flow velocity. But the research projects were fluid containing solid particles, and the conclusions obtained were closely related to the mechanical properties of solid particles. There are few studies on the induced corrosion of pure liquid-phase fluids.

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In this paper, the fluid-induced corrosion character of super 13Cr stainless steel is studied by changing the flow velocity, which is of great theoretical significance and useful value for preventing or slowing the occurrence of corrosion failure.

Experimental

Experimental System

The electrochemical reaction of metal surface was studied in a self-made jet system (Fig. 1). The experimental system included liquid storage tank, pump, magnetic flow meter (8712HR, Rosemount Co., Ltd., America) and electrochemical workstation (CS310, Corrtest, Co., Ltd.).

The three-electrode system consists of a saturated calomel electrode, a platinum electrode and a working electrode that was mounted on the bench. Before testing, samples were weighed using the electronic balance produced by Shanghai Liang Ping Instruments Co., Ltd. The precision of electronic balance is 0.1 mg. After the test is completed, the morphology, thickness and composition of the corrosion products are analyzed using JSM-6390

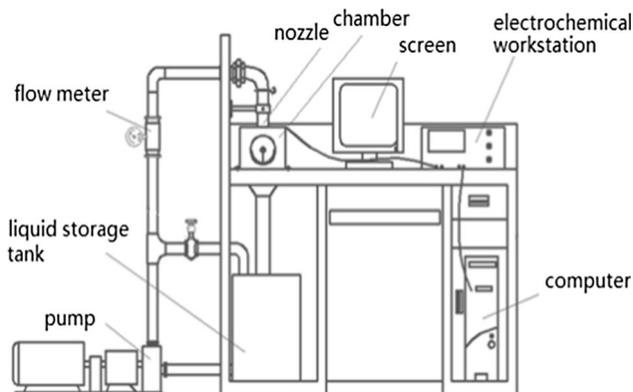


Fig. 1 Experimental setup

scanning electron microscope (SEM) produced by Japan Electronics company in Fig. 2.

Experimental Conditions

Solution

The concentration of Cl^- content was 21,239 mg/L, and the solutions used in the preparation were prepared by pure chemical reagent and distilled water.

Selection of Materials and Preparation of Samples

Super 13Cr stainless steel was selected as the research material, and the composition is shown in Table 1. The material was processed into rectangular blocks of length \times width \times height = 12.2 \times 6.4 \times 19 (mm). The copper wire was connected and then coated with epoxy resin to seal the other parts, leaving the working surface so that the erosion surface of the area of 0.78 cm^2 was exposed to the solution. The other surfaces were well packaged and insulated from the solution. Sealing operation should avoid the occurrence of gaps; otherwise, it would seriously interfere with the experimental results.

Test Electrode

The test electrode was super 13Cr stainless steel sample, and the material was processed into rectangular blocks. The saturated calomel reference electrode (SCE) which placed in the test chamber was connected to the erosion system by an electrolyte bridge. A long platinum wire was used as the counter electrode (CE).

Fluid Flow Velocity

The liquid flow velocity of this experiment was 0, 5.6, 9.6, 10.0, 14.8, 18.1, and 21.4 m/s.

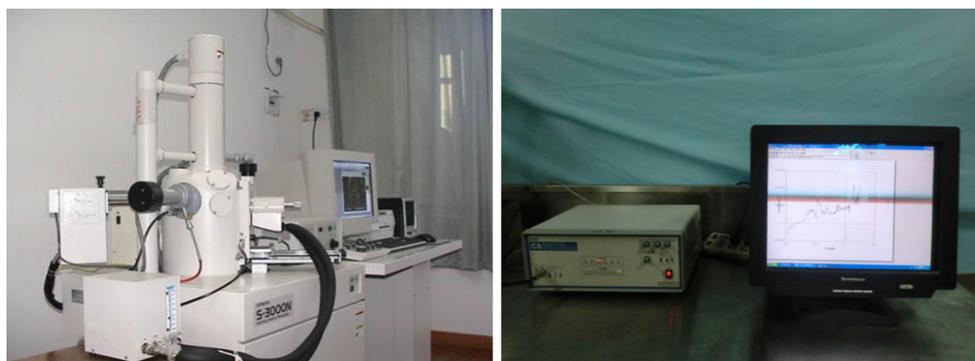


Fig. 2 SEM device and electrochemical workstation

Table 1 Chemical elemental weight (wt.%) steel for super 13Cr stainless steel

Steel	C	Si	Mn	P	S	Cr	Mo	Ni	Cu
Super 13Cr	0.022	0.22	0.45	0.015	0.001	12.79	0.92	4.34	0.51

Table 2 Super 13Cr linear polarization method to calculate the corrosion rate

Velocity (m/s)	R_p (Ohms cm^{-2})	I_o (A $\cdot 10^{-5}$)	E_o (V)	CR (mm/a)
0	1237	2.1089	-0.47529	0.2481
5.6	150	17.391	-0.07454	1.7662
9.6	160.43	16.26	-0.20804	1.9126
10.0	138.07	18.895	0.06974	2.2224
14.8	187.75	13.895	0.23325	1.6343
18.1	191.23	13.627	0.29482	1.6014
21.4	195.4	13.351	0.32427	1.5703

Experimental Procedure

Firstly, the test material was installed to the sample holder and injection angle was adjusted to 45°. Secondly, turning on the pump and waiting for a few minutes until the flow rate of the flow-meter is stable. The fluid temperature is measured at room temperature. Thirdly, electrochemical tests were performed. The open-circuit potential monitoring was carried out before the stable value was reached; then, the action potential polarization scanning was performed. And the sweep speed was set to 0.5 mV/s when the polarization curve was measured. The voltage range was set according to the material. The minimum range was -0.8 to +0.8 V relative to the open-circuit potential. Finally, the experimental data are collected after the test was completed.

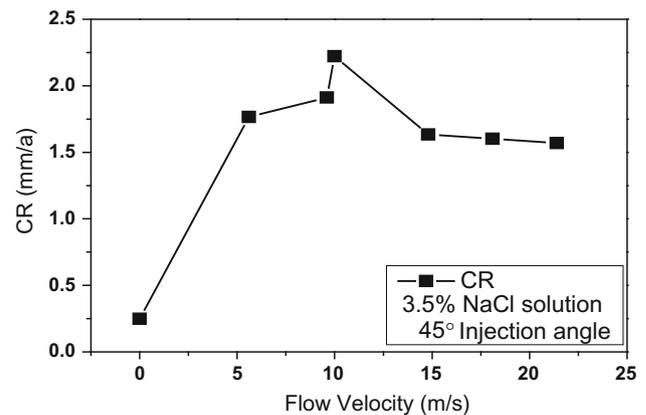
Results

According to the experimental design, the corrosion rate of 13Cr stainless steel at different flow velocities was measured when the injection angle was 45°.

Corrosion Rate

The effect of flow velocity on the corrosion rate is obtained by the linear polarization method, and the results are shown in Table 2 and Fig. 3.

The influence of the flow velocity in the range of 0–21.4 m/s on the corrosion rate was considered. It is observed from Fig. 3 that the flow velocity has a great

**Fig. 3** Effect of fluid flow velocity on corrosion rate of super 13Cr stainless steel

influence on the corrosion rate of super 13Cr stainless steel, and the corrosion rate tends to rise first and then decrease with the increase in flow velocity. It is observed from Fig. 3 that the corrosion rate gradually increases with the increase in flow velocity from 0 to 10.0 m/s. Then, it gradually decreases after a peak, and the corrosion rate reaches the peak at 10.0 m/s. In this experiment, it is observed that the corrosion rate of metal surface does not increase but decreases with the increase in flow velocity from 10.0 to 21.4 m/s. So 10.0 m/s should be the critical velocity of super 13Cr stainless steel corrosion.

Open-Circuit Potential

The open-circuit potential is one of the most simple and easy to obtain data for all corrosion criteria, which reflects the tendency of metals to dissolve in solution.

As shown in Fig. 4, as the flow velocity increases, the change of the open-circuit potential goes through a process of falling and then rising. The open-circuit potential is -0.32 V at the flow velocity of 5.6 m/s, and the open-circuit potential is -0.23 V when the flow velocity is increased to 9.6 m/s. It is observed from Fig. 4 that the open-circuit potential of the super 13Cr stainless steel reaches the minimum at 10.0 m/s. When the flow velocity was increased to 18.1 m/s, it was found that the open-circuit potential changed positively to -0.34 V. The open-circuit potential is greater at 21.4 m/s, indicating that the corrosion tendency of metal surface is lower and corrosion is not easy.

In this experiment, it is observed that the corrosion of metal surface is more serious with the increase in flow velocity, and the corrosion is most serious at 10.0 m/s flow velocity. And the direction of the whole change is in the negative direction.

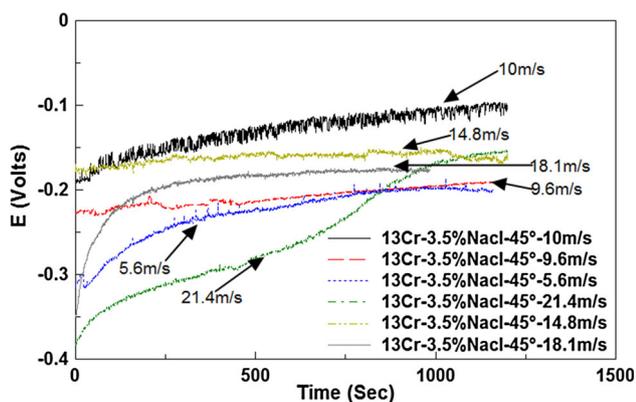


Fig. 4 Variation curves of open-circuit potential with time at different flow velocities

Polarization Curve

The polarization curve usually shows the relationship between the polarization potential and the polarization current. The polarization degree of the electrode can be seen very clearly from the polarization curve [15].

As shown in Fig. 5a, the trend of passivation is not obvious when the flow velocity is low. It shows that the anodic current density increases at the velocity of 9.6 m/s, which indicates the metal surface is in active state. In addition, it also shows that the current density of metal surface reaches the maximum at the velocity of 10.0 m/s, which indicates corrosion rate is the most serious at this time. As shown in Fig. 5b, the anodic polarization curve shows an obvious passivation trend when the flow velocity is in 21.4 m/s. It shows that the super 13Cr stainless steel can be passivated again, which leads to the decrease in corrosion rate.

In Fig. 6, the recovery potential of super 13Cr steel is in the passivation zone, which shows that super 13Cr steel has a certain ability of re-passivation. When the potential continues to rise, the metal anode current density will also have a peak value, and then, the anode current density will decrease again. As the potential increases, the current density rises after a trough. The trough of this current density is equivalent to the “re-passivation” of metal, that is, the surface of the metal is covered by a protective film again.

Discussion

Influence of Flow Velocity on Polarization Curve

In this experiment, at low flow velocities, due to the influence of hydrodynamic factors, the local rupture of the passive film on metal surface results in the dissolution and penetration corrosion of Cl⁻ steel. When the flow velocity

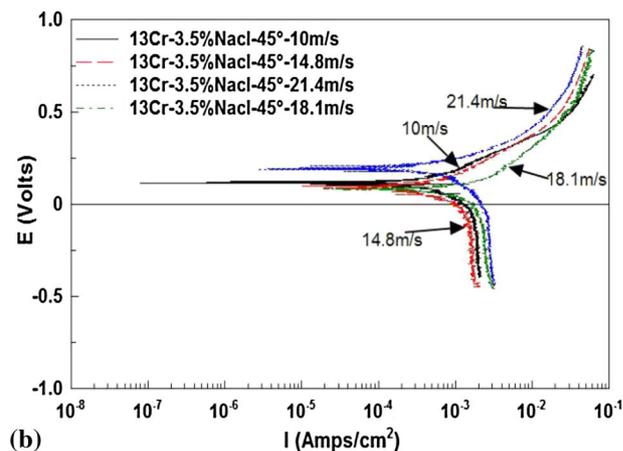
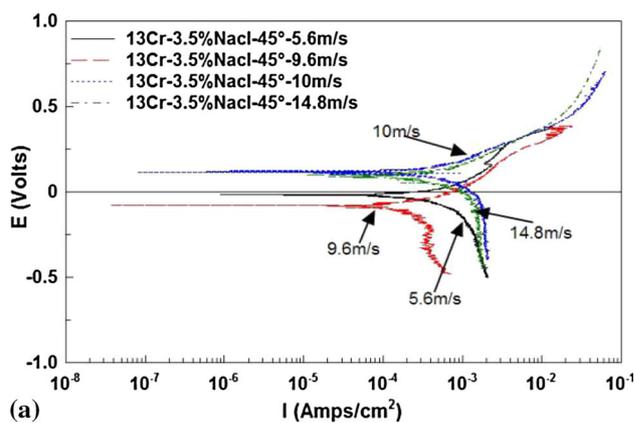


Fig. 5 Polarization curves of super 13Cr at different flow velocities. (a) 5.6, 9.6, 10, and 14.8 m/s and (b) 10, 14.8, 18.1, and 21.4 m/s

is in 10.0 m/s, due to the influence of hydrodynamic factors, the increase in wall shear stress caused by the high flow velocity leads to oxygen concentration diffusion layer thinning, and oxygen achieves a metal surface more and more, so that the flow corrosion rate increases. The flow velocity is in the 10.0–21.4 m/s range, the increase in flow velocity makes the shearing stress continue to increase, and the more oxygen is delivered to the electrode surface.

These conclusions were confirmed by Yong et al. [16]. The passivation of metal surface is caused by oxygen participating in anodic passivation reaction. The corrosion process is changed from cathode process control to anode control, which results in the decrease in corrosion rate with the increase in flow velocity. The results show that super 13Cr stainless steel has a certain ability of re-passivation.

Influence of Flow Velocity on Corrosion Morphology

Figure 7 shows the corrosion morphology at the velocity of 0, 5.6, 10.0, and 21.4 m/s. The corrosion product film of the sample is firstly dense and becomes loose and then becomes densification. Figure 7a indicates the corrosion

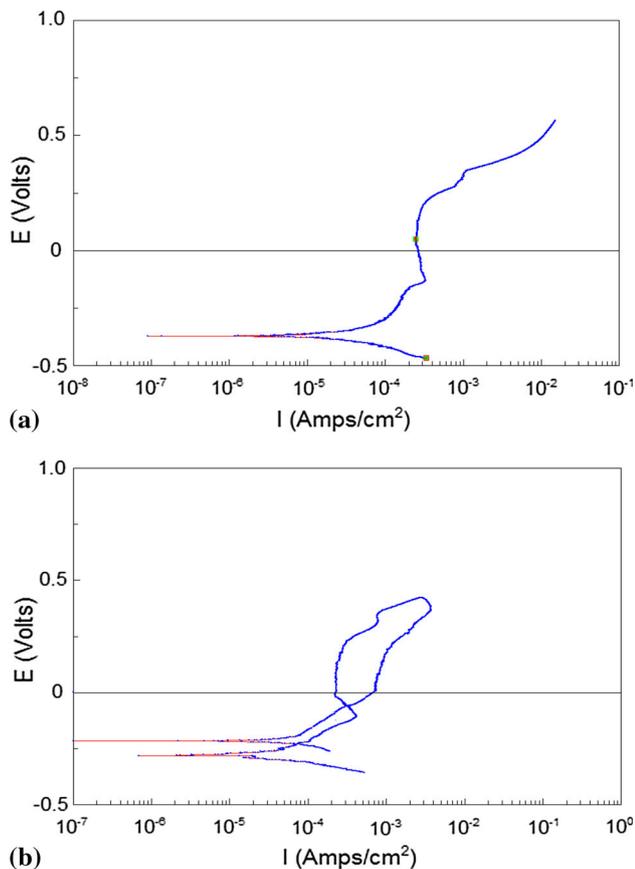


Fig. 6 Polarization curves and cyclic polarization curves at 14.8 m/s flow rate. (a) Polarization curve and (b) cyclic polarization curve

morphology at flow velocity of 0 m/s. The specimens show uniform corrosion, and the corrosion products adhered to the sample tightly and are more stable. At this time, the product film thickness is 23.3 μm . Figure 7b indicates the corrosion morphology at flow velocity of 5.6 m/s. The corrosion product film is obviously loose and microcracks appear. It is obvious observed that the product film thickness from the original 23.8 μm reduces to 17.8 μm . Figure 7c indicates the corrosion morphology at flow velocity of 10.0 m/s. As the flow velocity continues to increase, the corrosion products become more porous and less compact with the matrix, and the corrosion products are easily separated from the matrix.

By further amplification, it can be seen that the upper part is the corrosion product, the lower part is the metal matrix, and a boundary has been formed between them. At the demarcation line, it can be seen that the metal matrix has been corroded and formed loose tissue. At the moment, the thickness of the passive film reaches the minimum value of 9.71 μm . Figure 7d indicates the corrosion morphology at flow velocity of 21.4 m/s. As the flow rate

increases further, the corrosion product film begins to become densification. The thickness of the film is composed of 9.71 μm increased to 12.5 μm . The results show that the corrosion film formed at this time to prevent the diffusion of oxygen, and Cl^- cannot penetrate the corrosion product film which is hard to reach the bottom of the corrosion product film. These results lead to an increase in adhesion between the corrosion product film and the metal matrix, thereby preventing the oxygen diffusion reaction and causing the corrosion product film to become denser and firmly attached to the surface of the metal.

The comparison of the corrosion product membrane shows that the hydrodynamic factors have great effect on the corrosion of the specimen at the velocity of 10.0 m/s. At this point, the experimental results of the corrosion passive film is loose porous, and membrane damage is more serious. It is easy to make the product film and matrix fall off and accelerate the corrosion of the corrosive medium to the matrix, thus causing serious corrosion weight loss. Through the analysis of corrosion morphology of super 13Cr steel, it can be further explained that super 13Cr steel has a certain ability of re-passivation.

Influence of Flow Velocity on Corrosion Rate

The study result indicates that the flow of the medium has two effects on the induced corrosion: the mass transfer effect and the surface shear stress effect [17]. Therefore, the fluid velocity plays an important role in the erosion process, which directly affects the mechanism of flow-induced corrosion. As shown in Fig. 3, in this experiment, flow velocity in the range of 0–10.0 m/s, the increase in wall shear stress caused by the high flow velocity leads to the rupture of passive films and the exposure of fresh metal in the corrosive media, which causes the increase in corrosion rate. The results have been studied by Yong et al. [18]. The oxygen concentration gradient increases with the increase in flow velocity for the pipe flow system, which results in oxygen rapidly pass to the solid surface and the increase in the corrosion rate.

The influence of critical flow velocity on corrosion of stainless steel metal materials mainly divided into two cases [19]. At low flow velocity, the increase in the flow velocity increases the mass transfer process of oxygen, increases the passivation and re-passivation ability, and leads to the metal passivation, while the corrosion is relatively weak. At high flow velocity, the increase in flow velocity makes the shearing stress continue to increase, and the more oxygen is delivered to the electrode surface. The passivation of metal surface is caused by oxygen participating in anodic passivation reaction. The corrosion process is changed from cathode process control to anode control, which results in the decrease in corrosion rate with

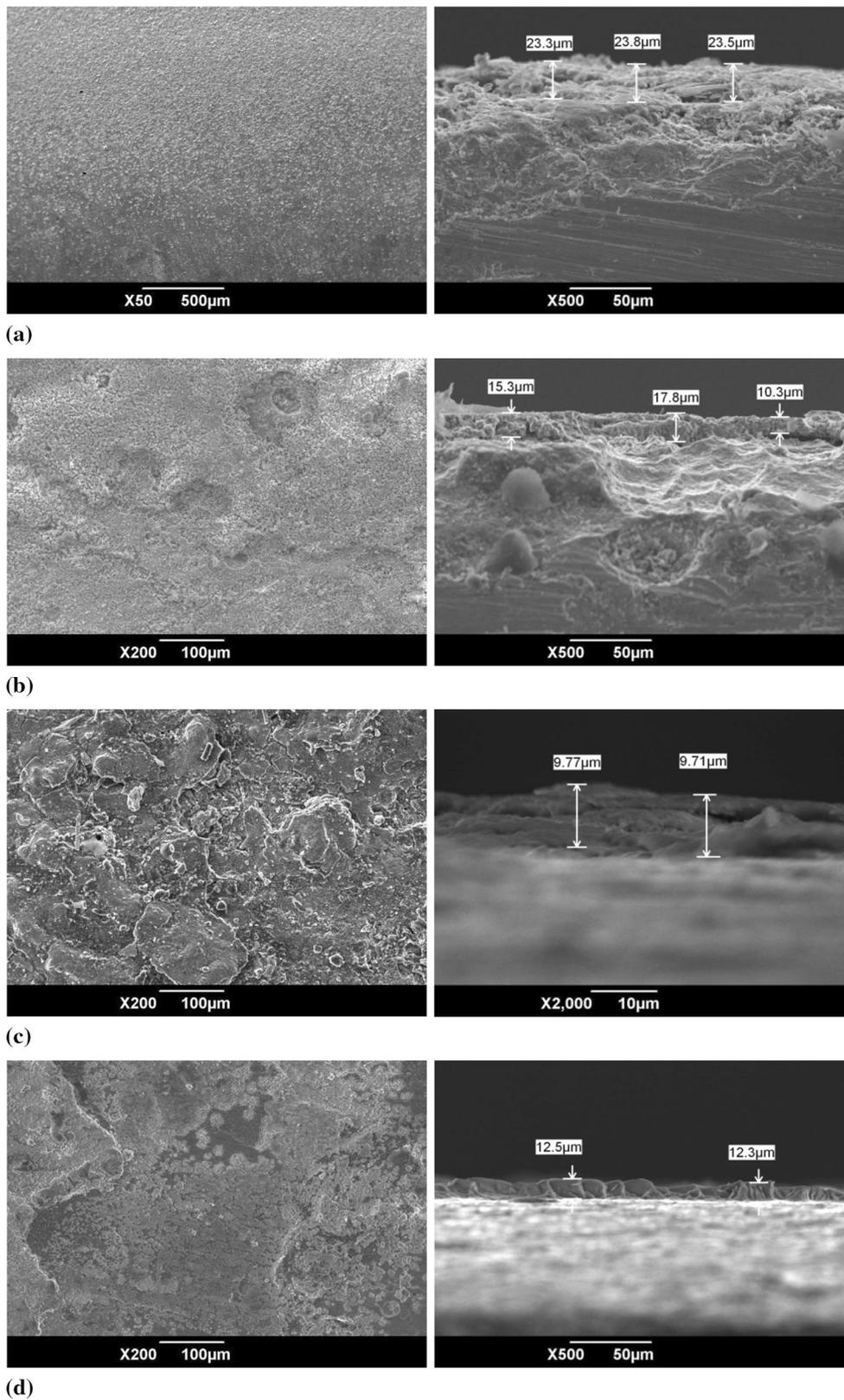


Fig. 7 Corrosion product film morphology of super 13Cr steel at different flow velocities. (a) 0 m/s, (b) 5.6 m/s, (c) 10.0 m/s, (d) 21.4 m/s

the increase in flow velocity. The results show that super 13Cr stainless steel has a certain ability of re-passivation.

In some cases, however, increasing the flow velocity can also reduce corrosion. Because the flow velocity is more than 10.0 m/s, the electrochemical reaction of the metal surface accelerates to form a passivation film, preventing the metal from contacting the chloride ions in the solution, resulting in a decrease in the corrosion rate. Under adding corrosion inhibitors this circumstance, higher flow velocities can increase the supply of chemicals on the metal surface, accordingly increasing the efficiency of the inhibitor to mitigate corrosion.

Conclusion

The conclusions derived from the present study can be summarized as follows:

1. The corrosion rate of super 13Cr stainless steel is very prominently influenced by the variation of the flow velocity. The corrosion rate gradually increases with the increase in flow velocity from 0–10.0 m/s. Then, it gradually decreases after a peak, and the corrosion rate reaches the peak at 10.0 m/s.
2. The change of speed imposes a significant impact on the open-circuit potential. The change tendency of the open-circuit potential shows it decreases first and then increases with the increase in the flow velocity of the fluid. The open-circuit potential of the super 13Cr stainless steel reaches the minimum at 10.0 m/s. And the direction of the whole change is in the negative direction.
3. The current density value of metal surface reaches the maximum at the velocity of 10.0 m/s, which indicates corrosion rate is the most serious at this time. When the flow velocity is more than 10.0 m/s, however, the corrosion rate decreases with the increasing flow velocity. The results show that super 13Cr stainless steel has a certain ability of re-passivation. The passivation of metal surface is caused by oxygen participating in anodic passivation reaction.

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