SCC behavior and susceptibility prediction mode of SMA490BW weathering steel under cathodic potential

Qiang Zeng1,2, Zhenghong Fu*, Bangjian Yang1, Guoqing Gou1, Hui Chen1 and ShaoWei Zhu4

1 Sichuan University of Arts and Science, Dazhou, 635000, People’s Republic of China
2 Intelligent Manufacturing Technology Research Institute of Dazhou, Dazhou, 635000, People’s Republic of China
3 Key Laboratory of Advanced Technologies of Materials, Ministry of Education China, Southwest Jiaotong University, Chengdu, 610031, People’s Republic of China
4 Chengdu Aircraft Industrial (Group) Co., Ltd, Chengdu, 610092, People’s Republic of China

E-mail: fuzhenghong@my.swjtu.edu.cn

Keywords: SMA490BW steel, SCC, anodic dissolution, hydrogen embrittlement, charge transfer resistance

Abstract

SMA490BW weathering steel has been used to manufacture high speed train bogie structures. However, its stress corrosion cracking (SCC) behavior was not very clearly, let alone the prediction mode. In this work, combined with fracture surface analysis by SEM, electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization analysis, the SCC behavior of SMA490BW steel in 3.5 wt.% NaCl solution under cathodic potentials from open circuit potential (OCP) to −1200 mV SCE (SCE = saturated calomel electrode) was studied using slow strain rate tensile (SSRT) method at 25 °C. The results indicated that the SCC susceptibility index (I_SSCRT) decreased with the applied potential negative shift from OCP (I_SSCRT = 0.31) to −800 mV SCE (I_SSCRT = 0.11) by anodic dissolution (AD) mechanism, and then sharply increased with the potential negatively increasing (I_SSCRT = 0.41 at −1200 mV SCE) by hydrogen embrittlement (HE) mechanism. The SCC susceptibility could be preliminarily predicted using the mode founded as a function of charge transfer resistance (R_t): I_SSCRT = 0.329 × exp −R_t / 2840.965 + 0.086. This study will be helpful for the service assessment of high speed train bogie structure and other structures manufactured by SMA490BW steel.

1. Introduction

SMA490BW steel is a type of low alloy high strength weather steel manufactured according to JIS- G3114-2008 standard. It is widely used on bridges, constructions and other structure components due to the perfect strength and weldability. SMA490BW steel is also the optimizing material for the high speed train bogie structures [1−3], and its structural integrity directly concerns the safely service of high speed train. In December 2017, a Shinkansen train was found serious cracking on bogies. If the crack furtherly propagates 30 mm, the bogie structure will completely failure and lead to serious derailment accident. This crack is not only caused by manufacture problems, stress corrosion cracking (SCC) and/or hydrogen induced stress corrosion cracking (HISCC) are also main factors.

SCC is a localized corrosion failure form subject to tensile load and specific corrosive environment for a SCC susceptive metal [4, 5]. In SMA490BW weathering steel, Cu, P, Cr and Ni is added as main alloying element to effectively resist the corrosive medium contacting with the steel by forming dense and well adhesive rust layer. But in marine atmosphere, the protective rust layer is hard to form due to the effects of Cl− [6]. Hydrogen evolution may appear during the corrosion reaction on the steel surface was controlled by cathodic polarization, and resulted in hydrogens adsorb on the steel surface and diffuse into the steel. The hydrogens aggregate in the defects traps such as inclusions, grain boundaries, and dislocations, induced decohesion and/or local high hydrogen pressure, facilitate the hydrogen-induced micro-cracks initiation and propagating and result in hydrogen embrittlement (HE), which is regarded as a main mechanism of SCC [7−10]. The SCC behavior is also
Table 1. Chemical composition of SMA490BW weathering steel (wt.%).

| Material    | C    | Si   | Mn   | S    | P    | Ni   | Cr   | Cu   | Fe  |
|-------------|------|------|------|------|------|------|------|------|-----|
| SMA490BW    | 0.091| 0.470| 1.410| 0.005| 0.035| 0.180| 0.480| 0.310| Bal.|

strongly dependent on the microstructures [11, 12]. For example, pearlite was considered to be susceptible to HE due to its layered structure [13–15].

Electrochemical methods have been used for the SCC mechanism and protective potential prediction. The electrochemical properties of the crack tip and crack wall could be respectively represented using polarization curves with fast and slow sweep rate. Thus, the SCC mechanism of a material can be primarily determined by the difference of the polarization curves [16, 17]. Charge transfer resistance \( (R_t) \) measured by electrochemical impedance spectroscopy (EIS) was performed for the protective potential prediction of metals [14, 18]. However, there is no mode was found to predict the SCC susceptibility using the corrosive parameters measured by electrochemical analysis.

Many studies have been applied on the general corrosion properties of weather steels, mainly about the effect of alloying elements and/or corrosive environment [19–22]. However, the SCC behavior of this type of steels is still not clear, let alone the prediction mode.

In the present work, SCC behavior of SMA490BW steel in 3.5 wt.% NaCl solution under various applied cathodic potentials from open circuit potential (OCP) to \( -1200 \text{ mV}_{\text{SCE}} \) (SCE = saturated calomel electrode) was studied by slow strain rate tensile (SSRT) method at 25 °C. Fracture surface analysis by SEM, potentiodynamic polarization and EIS analysis were used to study the SCC mechanism. And a SCC susceptibility prediction mode for SMA490BW steel was also founded as a function of \( R_t \).

2. Materials and experiment methods

Hot rolled SMA490BW weathering steel was used in this study. The chemical composition (wt.%) is listed in table 1. The addition of Ni, Cr and Cu improved its corrosion resistance. Optical metallography on the cross section etched by nital (figure 1(a)) shows banded shape pearlite and ferrite.

According to Liu [16] and Zhang [17], in corrosive environment, the crack wall could be fully polarization and in a quasi-stable state, the fresh crack tip was in a nonequilibrium state. Thus, the SCC mechanism of a material can be primarily determined by the difference of slow and fast sweep rate polarization curves. Figure 1(b) shows the potentiodynamic polarization curves of SMA490BW steel with a slow sweep rate of 0.1 mV s\(^{-1}\) and fast sweep rate of 10 mV s\(^{-1}\) in 3.5 wt.% NaCl solution at 25 °C. The whole potential range could be divided into three zones at \(-530 \text{ mV}_{\text{SCE}}\) and \(-1040 \text{ mV}_{\text{SCE}}\). At the potential above \(-530 \text{ mV}_{\text{SCE}}\) (Zone I), the SCC cracks initiation and propagation promoted by anodic dissolution (AD) mechanism due to both the crack wall and crack tip were in the anodic polarization state. At the potential between \(-530 \text{ mV}_{\text{SCE}}\) and \(-1040 \text{ mV}_{\text{SCE}}\) (Zone II), the hydrogen evolution reaction occurs but not very tempestuous while the AD reaction turns slower. So the susceptibility is not high in this zone. When the potential is below \(-1040 \text{ mV}_{\text{SCE}}\) (Zone III), tempestuous hydrogen evolution reaction occurs at both crack tip and wall, resulting in high SCC susceptibility by HE mechanism.

Based on the difference between polarization curves with fast and slow sweep rate, SSRT tests at a strain rate of \( 1 \times 10^{-6} \text{ s}^{-1} \) controlled by a SSRT test machine were conducted in 3.5 wt.% NaCl solution at 25 °C. Typical circular cross section specimens (figure 1(c)) with a gauge length of 22 mm were used according to ISO 7539-7-2005 standard. The referred to SCE potentials of OCP (\(-553 \text{ mV}_{\text{SCE}}\), \(-600 \text{ mV}_{\text{SCE}}\), \(-800 \text{ mV}_{\text{SCE}}\), \(-1000 \text{ mV}_{\text{SCE}}\)) and \(-1200 \text{ mV}_{\text{SCE}}\) were applied on the specimen by three-electrodes system using CHI 660C Electrochemical Workshop as shown in figure 1(d), where a platinum sheet worked as auxiliary electrode, saturated calomel electrode worked as reference electrode, the specimen itself acted as work electrode. As shown in figure 1(e), cathode reaction occurred and resulted in hydrogen atoms adsorbed and diffused into the steel when applied cathodic potential on the specimens during SSRT tests.

The SCC susceptibility index \( I_{\text{SSRT}} \) was used to compare the SCC susceptibility of SAM490BW steel under different applied cathodic potentials, which could be calculated using equation (1):

\[
I_{\text{SSRT}} = 1 - \frac{\sigma_{\text{fi}} \times (1 + \delta_{\text{fi}})}{\sigma_{\text{fa}} \times (1 + \delta_{\text{fa}})}
\]

where \( \sigma_{\text{fi}} \) and \( \sigma_{\text{fa}} \) respectively are the fracture strength in corrosive and inert environment. \( \delta_{\text{fi}} \) and \( \delta_{\text{fa}} \) are the elongation in corrosive and inert environment, respectively. SCC susceptibility increases with \( I_{\text{SSRT}} \) increasing.
The fracture side and surface morphologies were also examined after SSRT tests using optical microscope (Zeiss Stemi 2000-C) and SEM (QUANTA FEC 250). EIS test was performed to measure out the electrode reaction process. It was carried out under the potentials as same as that applied on SSRT tests with frequencies from 100 kHz to 0.01 Hz. Ten points per tenfold frequency was chosen, and 5 mV perturbation amplitude was set. The EIS test specimens were covered by epoxy resin and a 1 cm² area was exposed as the test surface. Before EIS test, the exposed surface was grinded and followed by polishing using silicon carbide polishing paste with a particle size of 2.5 μm. The corrosion parameters were fitted using Zview3.0a software. The test under various potentials was repeated tress times.

3. Results and discussions

3.1. EIS analysis

The Nyquist plots versus applied cathodic potential resulted from EIS tests are shown in figure 2(a). All Nyquist plots exhibit a single depressed semi-circle. The semi-circles diameters increase gradually with the potential negatively increasing from OCP to −800 mV_{SCE} and sharp decrease observed when the applied potential negatively increasing from −800 mV_{SCE} to −1400 mV_{SCE}. Figure 2(b) shows the electrical equivalent circuit, where \( R_s \) is the solution resistance, \( Q \) is capacitance and \( R_t \) is the charge transfer resistance. The \( R_t \) was obtained by conducting spectra fitting with the equivalent circuit depended on the potentials. Similar to the diameters of the Nyquist semi-circle plots, \( R_t \) increased with the potential negatively increasing from OCP to −800 mV_{SCE} and decreased with the potential negatively increasing from −800 mV_{SCE} to −1400 mV_{SCE} (figure 2(b)).

In this study, the electrode reactions only have one status variable, applied potential (E). In this status, the EIS only exhibited one time constant during each electrode reaction was performed separately. Thus, the Faraday admittance (\( Y_{FE} \)) expressed as:
Where $I_{Ft}$ is Faraday current density, $R_t$ is charge transfer resistance. During each electrode reaction was performed separately, there is also only one capacitive reactance arc. When the two reactions occurred simultaneously, the total Faraday admittance ($Y_F$) could be expressed as:

$$Y_F = Y_{F1} + Y_{F2} = \frac{1}{R_{t1}} + \frac{1}{R_{t2}} = \frac{1}{R_t}$$

Thus, $R_t$ could be divided into two parts: anodic ($R_{ta}$) and cathodic ($R_{tc}$) charge transfer resistance (figure 3(a)). With the potential negatively increasing from OCP to $-800$ mV$_{SCE}$, $R_{ta}$ increased rapidly due to the anodic overpotential reduction. However, $R_{tc}$ decreased slightly due to the cathodic overpotential enlarging. Thus the $R_t$ increase gradually as a combined result and got the peak value at $-800$ mV$_{SCE}$ (figure 2(b)), where the cathodic reaction was controlled by oxygen concentration. Subsequently, the hydrogen evolution reaction was strongly assisted with the applied potential moved to more negative from $-800$ mV$_{SCE}$ to $-1400$ mV$_{SCE}$. Here, the $R_t$ could be divided into another two parts (figure 3(b)): oxygen reduction reaction charge transfer resistance ($R_{tO}$) and hydrogen evolution reaction charge transfer resistance ($R_{tH}$). The charge transfer resistance of the cathodic reaction notably increased owning to the occurring of hydrogen evolution reaction. As a result, $R_t$ declined rapidly with the potential shifting from $-800$ mV$_{SCE}$ to $-1400$ mV$_{SCE}$.

**Figure 2.** EIS analysis results: (a) Nyquist plot, (b) charge transfer resistance ($R_t$) as the function of applied potential.

**Figure 3.** Equivalent electrical circuit: (a) weak cathodic polarization and (b) strong cathodic polarization.

$$Y_F = \left(\frac{\partial I_{Ft}}{\partial E}\right)_0 = \frac{1}{R_{ti}} \quad i = 1, \ 2$$

Therefore, the electrochemical impedance spectrum of the whole electrode also has only one time constant and capacitive reactance arc.
As a result, the $R_t$ got the peak value at $-800\text{ mV}_{\text{SCE}}$, at where the anodic dissolution was inappreciable, the cathodic reaction was controlled by oxygen concentration with weak hydrogen evolution reaction. Therefore, the SMA490BW steel could both be prevented from AD and avoid HE. As the potentials turned more negative than $-800\text{ mV}_{\text{SCE}}$, the $R_t$ was sharply reduced, suggesting hydrogen evolution reaction enhancement. These results were consistent with that of potentiodynamic polarization test (figure 1(b)).

### 3.2. SSRT tests

The SSRT stress-strain curves of SMA490BW steel measured in air and in 3.5 wt.% NaCl solution under various cathodic potential are shown in figure 4(a). Obviously, the corrosive environment and cathodic potential have prominent effects on the SCC behavior of SMA490BW steel. To be more specific, as shown in figure 4(b), the fracture strain values at OCP and various cathodic potential were lower than that in air. It is worth noting that the fracture strain increased slowly from OCP to $-800\text{ mV}_{\text{SCE}}$ and reached the peak value at $-800\text{ mV}_{\text{SCE}}$. Whereafter, the fracture strain decreased sharply with the potential negative shift from $-800\text{ mV}_{\text{SCE}}$ to $-1200\text{ mV}_{\text{SCE}}$. Except at OCP, the fracture strength shows almost no obvious change in air and other various cathodic potential. And the fracture strength shows obvious reduce at OCP is due to the pits initiation and propagation induced by AD. However, as many results from other studies\[7–10], the fracture strength always exhibited little change but heavily decreasing of fracture strain during HE.

The fast and slow sweep rate polarization curves (figure 1(b)) shows that the SCC mechanism at OCP is controlled by AD, which may decreases the strength sharply\[17, 23]. With the potential turn to negative, the SCC behavior is mainly controlled by HE mechanism and decreases the elongation\[14, 16, 24].

Overall considering the effects of corrosive environment and cathodic potentials on the fracture stain and strength, SCC susceptibility index $I_{\text{SSRT}}$ as the function of applied potential calculated by equation (1) is shown in figure 5. The $I_{\text{SSRT}}$ versus potential curve exhibited as a ‘V’ shape and has the lowest value of 0.11 at $-800\text{ mV}_{\text{SCE}}$, which is about 3 times lower than that of OCP ($I_{\text{SSRT}} = 0.31$), and 4 times lower than that of $-1200\text{ mV}_{\text{SCE}}$ ($I_{\text{SSRT}} = 0.41$).

Figure 6 shows the typical fracture surface SEM images after SSRT tests in air, OCP, $-800\text{ mV}_{\text{SCE}}$ and $-1200\text{ mV}_{\text{SCE}}$. The micro-morphologies exhibit ductile failure features of dimples, whereas the morphologies at OCP and $-1200\text{ mV}_{\text{SCE}}$ show brittle rupture of quasi-cleavage features. Thus indicating that the SMA490BW steel has a certain degree of SCC susceptibility at OCP and $-1200\text{ mV}_{\text{SCE}}$ in 3.5 wt.% NaCl solution, and that the susceptibility was greatly lowered at $-800\text{ mV}_{\text{SCE}}$. These results are consistent with the results of SCC susceptibility in figure 5. Although both of the fracture surface ruptured at OCP and $-1200\text{ mV}_{\text{SCE}}$ exhibited quasi-cleavage features. It should be pointed out that many corrosion products could be observed on the fracture surface ruptured at OCP, indicating that the SCC mechanism is anodic dissolution. However, there is almost no corrosion products could be observed on the fracture surface ruptured at $-1200\text{ mV}_{\text{SCE}}$, indicating that the SCC mechanism is HE.

The OM images on the side face near the fracture surface are shown in figure 6. Corrosion pits could be observed on the specimen ruptured at OCP, and cracks initialed from these corrosion pits (figure 7(a)). While on the specimen ruptured at $-800\text{ mV}_{\text{SCE}}$, the side face exhibited some deformation steps near the fracture surface instead of corrosion pits and cracks (figure 7(b)). When the potential was negative to $-1200\text{ mV}_{\text{SCE}}$, a large amount of cracks could be observed on the side face near the fracture surface without any pits (figure 7(c)).
3.3. Fracture mode

The reaction process on the steel surface at various potentials analyzed by EIS indicated that the steel will be well protected at −800 mV_{SCE} because both of the anodic dissolution and cathodic hydrogen evolution reaction are very weak. As a result, the steel showed almost no SCC susceptibility (ISSRT = 0.11) and still kept excellent plasticity with ductile fracture characterize of dimples as same as that in air.

At OCP condition, the steel exhibited very strong SCC susceptibility due to the AD mechanism [14, 17]. Figure 6 gives out the schematic of SCC failure controlled by AD mechanism. During AD process, corrosion pits will form on the specimen surface and induce the stress concentration at the bottom of the pits [25]. As a result,
Figure 7. OM images on the side face near the fracture surface: (a) cracks initial from corrosion pits at OCP, (b) deformation steps on the specimen ruptured at $-800 \text{ mV}_{\text{SCE}}$ and (c) a large amount of cracks on the specimen ruptured at $-1200 \text{ mV}_{\text{SCE}}$.

Figure 8. Schematic of SCC failure controlled by anodic dissolution mechanism.
the micro-cracks will initiate and propagate under the external load. Therefore, the fracture surface presented as a quasi-cleavage feature \[26\].

With the potential negative to \(-1200\) mV_{SCE}, as shown in figure 9(a), drastic hydrogen evolution reaction observed on the specimen surface. The hydrogen evolution reaction in applied cathodic potential is as follow:

\[
\text{H}_2\text{O} + e^- \rightarrow \text{H}_{\text{ads}} + \text{OH}^- \tag{5}
\]

Where \(\text{H}_{\text{ads}}\) is the hydrogen atoms adhere on the specimen surface. Subsequently, the \(\text{H}_{\text{ads}}\) penetrated into the steel and diffused due to its thermal motion. Hydrogen atoms intend to aggregate in the traps such as impurities, grain boundaries and dislocations, inducing dehesion and/or produced high hydrogen partial pressure \[27–29\]. This may initiate and propagate the hydrogen-induced micro-cracks in these traps, resulting in HE failure. When micro-cracks initiated, hydrogen atoms will diffuse to the crack tip and reach great high concentration (figure 9(b)). Thus the cracking rate was ulteriorly enhanced. As a result, the steel showed skyscraping SCC susceptibility at \(-1200\) mV_{SCE} (\(I_{SSRT} = 0.41\)) and exhibited quasi-cleavage feature and secondary cracks on the fracture surface.

### 3.4. SCC susceptibility prediction mode

The charge transfer resistance \(R_t\) and SCC susceptibility index \(I_{SSRT}\) as a function of applied potentials is shown in figure 10(a). \(R_t\) value increased gradually with the potential negatively increasing from OCP to \(-800\) mV_{SCE}, and sharply decreased with the potential negatively increasing from \(-800\) mV_{SCE} to \(-1400\) mV_{SCE}. On the
contrary, the $I_{SSRT}$ value decreased gradually as the potential negatively increasing from OCP to $-800 \text{ mV}_{SCE}$ and increased sharply when the potential negatively increasing from $-800 \text{ mV}_{SCE}$ to $-1200 \text{ mV}_{SCE}$. Therefore, the relationships between $R_t$ and applied potentials, $I_{SSRT}$ and applied potentials could be fitted using Gauss function:

$$y = y_0 + A \times \exp \left( \frac{(x - x_0)/w}{-2} \right)$$

where $y_0$, $A$, $x_0$ and $w$ are fitting constant and the values, and fitting variance $R^2$ are listed in Table 2. Here, we suppose all the parameters as dimensionless. The fitting $R^2$ for $R_t$ and $I_{SSRT}$ are 0.94 and 0.96 respectively, which indicating that the function is suitable for fitting the experiment results.

Calculating $x$ in equation (3):

$$x = x_0 + w \sqrt{-2 \ln \frac{y - y_0}{A}}$$

(7)

Here, ordering $y$ as $R_t$ and $I_{SSRT}$ respectively. When at the same applied potential, equation (4) could be rewrite as:

$$x_{t0} + w_I \sqrt{-2 \ln \frac{I_{SSRT} - y_{t0}}{A_t}} = x_{R0} + w_r \sqrt{-2 \ln \frac{R_t - y_{R0}}{A_R}}$$

(8)

Plugging the fitting constant in Table 1 into equation (6), we can found a function between $I_{SSRT}$ and $R_t$:

$$I_{SSRT} = A \times \exp \frac{-R_t}{t} + B$$

(9)

Using equation (7) to fit the experimental data $I_{SSRT}$ and $R_t$ for calculating the constants $A$, $B$ and $t$, as shown in figure 10(b) and equation (8). Thus, the SCC susceptibility prediction mode for SMA490BW steel is founded. And the $R^2$ value is 0.89, which indicated that this mode is suitable for the prediction.

The SCC susceptibility data of E690 steel in [14] was also fitted using equation (9) and shown in figure 11 and equation (11). The fitting variance $R^2$ value is 0.84, indicating that this mode is also suitable for the SCC susceptibility prediction of other steels.

### Table 2. Fitting constant and the values and fitting variance.

| Fitting constant | $y_0$ | $A$ | $x_0$ | $w$ | $R^2$ |
|------------------|-------|-----|-------|-----|-------|
| $R_t$            | 345.40| 5654.00 | $-823.17$ | 119.28 | 0.94 |
| $I_{SSRT}$       | 0.43  | $-0.33$ | $-769.53$ | 180.22 | 0.96 |

![Figure 11. Fitting resultes of E690 steel SCC susceptibility data in [14] using equation (9).](image)
4. Conclusions

In summarizing, the SCC behavior of SMA490BW steel under various applied potentials was investigated by SSRT method and electrochemical analysis.

(1) The SCC susceptibility decreased from with the applied potential negative shift from OCP to $-800 \text{ mV}_{\text{SCE}}$ by AD mechanism, and then increased sharply with the potential turn to more negative by HE mechanism.

(2) A SCC susceptibility prediction mode was found as a function of $R_t$: $I_{\text{SSRT}} = 0.305 \times \exp\left(-\frac{R_t}{438.178}\right) + 0.216$

(11)

Acknowledgments

The authors would like to acknowledge the financial support from the National Key Research and Development Program of China (No. 2016YFB1200602–16).

ORCID iDs

Zhenghong Fu @ https://orcid.org/0000-0002-7616-965X

References

[1] He B, Deng H, Jiang M, Wei K and Li J 2017 Effect of ultrasonic impact treatment on the ultrahigh cycle fatigue properties of SMA490BW steel welded joints The International Journal of Advanced Manufacturing Technology 96 1571–7

[2] Lu Y, Xiang P, Dong P, Zhang X and Zeng J 2018 Analysis of the effects of vibration modes on fatigue damage in high-speed train bogie frames Eng. Fail. Anal. 89 222–41

[3] Chen B, Zhao Y and Yang B 2012 Scale-induced effects on fatigue properties of a cast steel for bogie frames of China railway rolling wagons Int. J. Fatigue 35 45–55

[4] Liu X Y, Kameda J, Anderegg J W, Takaki S, Abiko K and McMahon C J 2008 Hydrogen-induced cracking in a very-high-purity high-strength steel Materials Science and Engineering: A 492 188–20

[5] Fu Z H, Gou G Q, Xiao J, Qu Y S and Wang W J 2017 The effect of potential on the SCC behavior of AISI301L stainless steel welded joints in 3.5% NaCl solution Int. J. Mod. Phys. B 31 1744048

[6] Wu W, Cheng X, Hou H, Liu B and Li X 2018 Insight into the product film formed on Ni-advanced weathering steel in a tropical marine atmosphere Appl. Surf. Sci. 436 80–9

[7] Elboudjaini M and Revie R W 2009 Metallurgical factors in stress corrosion cracking (SCC) and hydrogen-induced cracking (HIC) J. Solid State Electrochem. 13 1091–9

[8] Guo J X, Li J X, Qiao L J, Gao K W and Chu W Y 2003 Stress corrosion cracking and hydrogen-induced cracking of amorphous Fe74:5Ni10Si3:5B9C2 Corros. Sci. 45 735–45

[9] Chattoraj J 2011 Stress corrosion cracking in stress corrosion cracking (SCC) and hydrogen-assisted cracking in titanium alloys Woodhead Publishing Series in Metals and Surface Engineering 381–408

[10] McGuin K F and Aballe M 2013 Hydrogen induced SCC and caustic cracking of cold drawn prestressing tendon Br. Corros. J. 17 15–7

[11] Prawoto Y, Moin A, Tadjuddin M and Wan Nik W B 2011 Effect of microstructures on SCC of steel: field failure analysis case study and laboratory test result Eng. Fail. Anal. 18 1858–66

[12] Hejazi D, Haq A J, Yazdipour N, Dunne D P, Calka A, Barbaro F and Pereloma E V 2012 Effect of manganese content and microstructure on the susceptibility of X70 pipeline steel to hydrogen cracking Materials Science and Engineering: A 551 40–9

[13] Beidokhti B, Dolati A and Koukabi A H 2009 Effects of alloying elements and microstructure on the susceptibility of the welded HSLA steel to hydrogen-induced cracking and sulfide stress cracking Materials Science and Engineering: A 507 167–73

[14] Ma H, Liu Z, Du C, Wang H, Li C and Li X 2015 Effect of cathodic potentials on the SCC behavior of E690 steel in simulated seawater Materials Science and Engineering: A 642 22–31

[15] Zitter H, Mori G, Hochtrlt G and Wieser H 2002 Evaluation of cpt values determined by astm g48 practice. report on round robin tests of the corrosion committee of the austria society of metallurgy Materials and Corrosion 53 37–43

[16] Liu Z Y, Li X G and Cheng Y F 2012 Mechanistic aspect of near-neutral pH stress corrosion cracking of pipelines under cathodic polarization Corros. Sci. 55 54–60

[17] Zhang L, Li X, Du C and Huang Y 2009 Effect of applied potentials on stress corrosion cracking of X70 pipeline steel in alkali solution Mater. Des. 30 2259–65

[18] Zhao T, Liu Z, Du C, Sun M and Li X 2018 Effects of cathodic polarization on corrosion fatigue life of E690 steel in simulated seawater Int. J. Fatigue 110 103–14

[19] Díaz I, Cano H, Lopezano P, de la Fuente D, Chicho B, Jiménez J A, Medina S F and Morcillo M 2018 Five-year atmospheric corrosion of Cu, Cr and Ni weathering steels in a wide range of environments Corros. Sci. 141 146–67

[20] Liu C, Revilla R I, Liu Z, Zhang D, Li X and Terryn H 2017 Effect of inclusions modified by rare earth elements (Ce, La) on localized marine corrosion in Q460NH weathering steel Corros. Sci. 129 82–90

[21] Zhou Y, Chen J, Xu Y and Liu Z 2013 Effects of Cr, Ni and Cu on the corrosion behavior of low carbon microalloying steel in a Cl– containing environment Journal of Materials Science & Technology 29 168–74
[22] Cheng X, Jin Z, Liu M and Li X 2017 Optimizing the nickel content in weathering steels to enhance their corrosion resistance in acidic atmospheres Corros. Sci. 115 135–42
[23] Nguyen T T, Bolivar J, Shi Y, Réthoré J, King A, Fregonese M, Adrien J, Buffiere J Y and Baietto M C 2018 A phase field method for modeling anodic dissolution induced stress corrosion crack propagation Corros. Sci. 132 146–60
[24] Zhu M, Du C, Li X, Liu Z, Wang S, Li J and Zhang D 2014 Effect of AC current density on stress corrosion cracking behavior of X80 pipeline steel in high pH carbonate/bicarbonate solution Electrochim. Acta 117 351–9
[25] Tian W, Li S, Du N, Chen S and Wu Q 2015 Effects of applied potential on stable pitting of 304 stainless steel Corros. Sci. 93 242–55
[26] Mansoori H, Mirzaeir F, Esmaeilzadeh F, Vojood A and Dowrani A S 2017 Pitting corrosion failure analysis of a wet gas pipeline Eng. Fail. Anal. 82 16–25
[27] Uematsu Y, Kakiuchi T and Nakajima M 2012 Stress corrosion cracking behavior of the wrought magnesium alloy AZ31 under controlled cathodic potentials Materials Science and Engineering: A 531 171–7
[28] Bueno A H S, Moreira E D, Siqueira P and Gomes J A C P 2014 Effect of cathodic potential on hydrogen permeation of API grade steels in modified NS4 solution Materials Science and Engineering: A 597 117–21
[29] Arafin M A and Szpunar J A 2011 Effect of bainitic microstructure on the susceptibility of pipeline steels to hydrogen induced cracking Materials Science and Engineering: A 528 4927–40