Int. J. Electrochem. Sci., 8 **(2013)** 5539 - 5545

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Short Communication

38CrSi Corrosive Fatigue Crack Propagation Model by Various Polarization Potentials

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Received: 3 February 2013 / *Accepted:* 13 March 2013 / *Published:* 1 April 2013

By various polarization potentials，the corrosion fatigue crack propagation (CFCP) behavior of 38CrSi was investigated. It was found that the CFCP life decreases under the intense cathode polarization potentials and anodic polarization potentials. However, the CFCP life increases by cathode polarization potentials of -1000mV～-200mV.A model of the relationship between CFCP rate and polarization potential for 38CrSi was established. The average relative error between experimental and calculated CFCP rate was less than 10%.The results indicate that the model is satisfied with the engineering precision requirement completely.

Keywords: Corrosive fatigue, crack propagation, Polarization Potential

1. INTRODUCTION

38CrSi steel has high strength, high tenacity and weld property, which was used in amphibious vehicle extensively. But the corrosion fatigue life of 38CrSi in sea water environment was shorter than in air[1-5]. The life of CFCP was 90% of total corrosion fatigue life [6-7]. So it is important to investigate the CFCP of 38CrSi. The cathode protection method is commonly used in sea environment for high strength steel [8-9]. The cathode polarization potential variation influences the electrochemistry behavior in the crack area and the anode solution process directly. So it influences fatigue crack propagation rate indirectly. The corrosion fatigue life increases obviously when the cathode polarization potential controlled properly. In order to assure 38CrSi steel used in amphibious vehicle safely protected and its corrosion fatigue life fulfill the mission profile, the corrosion fatigue crack propagation (CFCP) behavior of 38CrSi under various polarization potentials was investigated. 38CrSi corrosive fatigue crack propagation model by various polarization potentials was established.

The results are important for 38CrSi material cathode protection designation and corrosion fatigue life prediction.

2. TEST METHOD

The specimen was 38CrSi plate, which thickness was 16mm and tension strength around 1000MPa[3].The specimen was three point bending specimen according to GB/T6398-2000. The dimension of it was 14mm×28mm×150mm. The notch depth was 5.8mm, which direction was perpendicular to rolling direction. The surface of the specimen was cleared with acet and dried with air. The area in NaCl solution part was 4.0cm^2 and the other part was pressurized with 704 pastern.

An electro-hydraulic servo fatigue testing machine MTS810 with maximum load 100kN made of American and potentiometer SI1287 made of Solartron Company were used in the test.

The specimen was fixed on the machine. The load amplitude applied on the specimen was 8.5kN with frequency 10Hz, stress ration R=0 to get the crack of 1.5mm at the initialization state.

The specimen was installed in the electrolytic cell [9]. Then it was fixed on the fatigue testing machine to perform corrosion fatigue crack propagation test. The cauterant was 3.5% NaCl solution. The fatigue load amplitude was controlled in the test and the stress ratio R was 0.1.The load form was sine wave and the maximum load was 8.5kN.The load frequency was 1Hz.The crack length was measured with COD.

Constant polarization potentials measurement system with three electrodes was used in the test. The specimen was working electrode. Saturation calomel electrode and platinum patch were used as reference electrode and assistant electrode. Electrolyte was 3.5% NaCl solution. The relationship between fatigue crack propagation speed and stress strengthen factor ($da/dN \sim \Delta K$) under various polarization potentials.

3. RESULTS AND DISCUSSION

3.1 CFCP of 38CrSi under various polarization potentials and fatigue life

Figure.1 was polarization curve of 38CrSi steel in 3.5% NaCl solution. ab was anodic polarization curve, which was controlled by metallic anode dissolution. be was cathode polarization curve, which was controlled by oxygen diffuse. Polarization potential at inflexion d was controlled by oxygen and hydrogen diffuse. The representative polarization potentials including -200mV、-300mV、-400mV、-800mV、-900mV、-1000mV、-1050mV、-1100mV and -1200mV were investigated in detail. Figure2.(a) shows the average of 38CrSi steel fatigue crack propagation rate with the stress strengthen factor between 19Mpa·m$^{1/2}$～85MPa·m$^{1/2}$ under 3.5% NaCl solution.The corrosive fatigue crack propagation life under various polarization potentials was shown in Figure.2(b). Figure2.(b) shows that the corrosive fatigue crack propagation life under -200mV、-300mV and -400mV conditions is shorter than under carve out a way polarization potential. At the same time $\overline{\frac{da}{dN}}$ increases. With polarization potential moves toward positive potential, $\overline{\frac{da}{dN}}$ of 38CrSi increases and corrosive fatigue life shortens obviously. $\overline{\frac{da}{dN}}$ of 38CrSi decrease under polarization potential -800mV、-900mV and -1000mV. The corrosive fatigue crack propagation life increases.

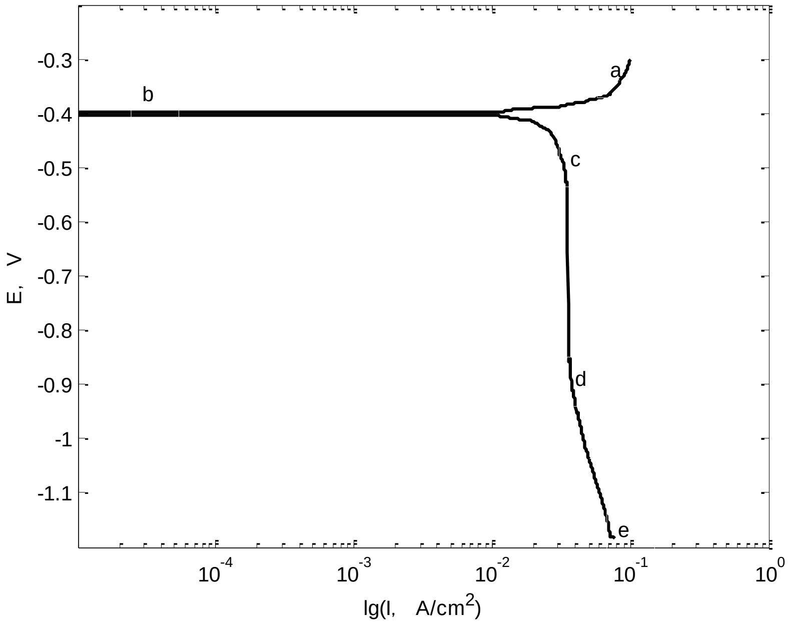

Figure 1. Polarization curve of 38CrSi steel in 3.5% NaCl solution

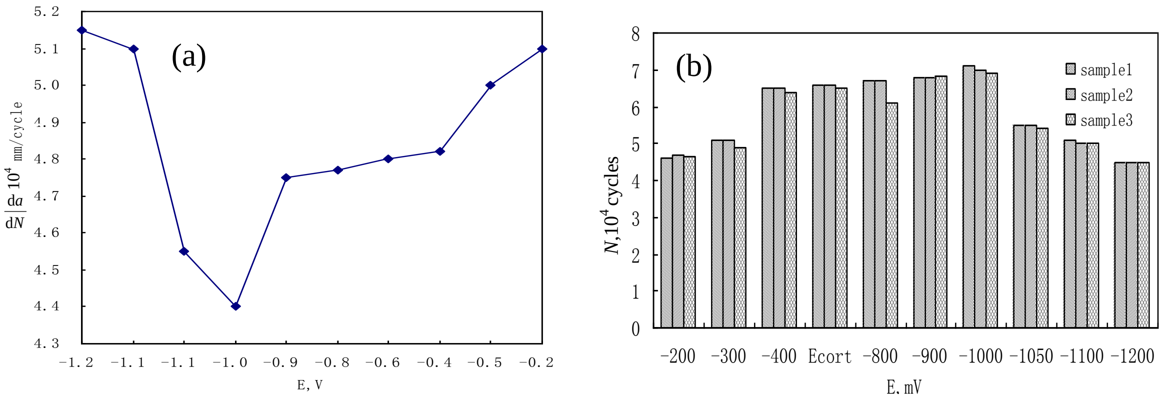

Figure 2. Average CFCP rate (a) and CFCP life (b) of 38CrSi by various polarization potentials

$\overline{\frac{da}{dN}}$ of 38CrSi increase under polarization potential -1200mV、-1100mV and -1050mV. The corrosive fatigue crack propagation life decreases obviously. Hydrogen generate at cathode when polarization potential -1200mV、-1100mV and -1050mV, which penetrate into metal easily. So the crack tip becomes fragility. Superfluous hydrogen evolution occurred at the crack tip and crack propagation rate $\overline{\frac{da}{dN}}$ increased.

3.2 Corrosion fatigue crack propagation model

3.2.1 Corrosion accelerated factor

The corrosion fatigue crack propagation rate in air is faster than in vacuum. Dry and clear air does small influence on metal fatigue crack propagation rate [10-13]. Paris empirical formula is often used in the condition, which was shown in formula (1).

$$\frac{da}{aN} = C(\Delta K)^m \qquad (1)$$

Dry air was taken as inert medium. Fatigue data under air condition was taken as standard compare to fatigue data under corrosion environment.

There are lots of factors influences on fatigue life including chemistry, load, metal processing technique etc. The material, shape of the specimen and the load applied on it were appointed in the test. The solution was stable. So the corrosion accelerated factor C_{cort} was used to modify the relationship between $\frac{\mathrm{d}a}{\mathrm{d}N}$ and ΔK. The data used in Paris formula obtained from the test data in dry air. In consideration the influence corrosive solution on fatigue cracks propagation, Paris empirical formula was modified as

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C \cdot C_{cort} \cdot (\Delta K)^m \qquad (2)$$

It is easily found that the corrosion accelerated factor C_{cort} was added into formula (1).In order to make a detailed discuss, formula (2) was changed as

$$\frac{\mathrm{d}a}{\mathrm{d}N}(E) = C(E) \cdot C_{air} \cdot (\Delta K)^{m_{air}} \qquad (3)$$

$\frac{\mathrm{d}a}{\mathrm{d}N}(E)$ is CFCP at a polarization potential. $C(E)$ is the corrosion accelerated factor related to polarization potentials. C_{air} is the regression analysis coefficient from fatigue crack propagation test data. m_{air} is the exponent. ΔK is amplitude of stress intensity factor.

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Take the fatigue crack propagation rate in air formula into formula (3) which is shown in Table 1. Formula (4) is got which shows the relationship between CFCP rate and stress intense factor in 3.5%NaCl solution. The unit of $\frac{\mathrm{d}a}{\mathrm{d}N}(E)$ is mm/cycle. The unit of stress intense factor is $\text{MPa}\cdot\text{m}^{1/2}$.

$$\frac{\mathrm{d}a}{\mathrm{d}N}(E) = C(E) \times 6.1965 \times 10^{-8} \times (\Delta K)^{2.3230} \qquad （4）$$

3.2.2 Corrosion accelerated factor C(E)

There is an optimal $C(E)$ at a certain polarization potential. CFCP is the nearest approximation of test result with the optimal $C(E)$.

$$F(E)=\sum_{i=1}^{p}\left\{\frac{\left[\frac{\mathrm{d}a}{\mathrm{d}N}(E)\right]_i-\left[\frac{\mathrm{d}a}{\mathrm{d}N}(E)\right]_i^s}{\left[\frac{\mathrm{d}a}{\mathrm{d}N}(E)\right]_i^s}\right\}^2 \qquad （5）$$

The optimal $C(E)$ is corrosion accelerate factor. In order to get it, a concept named relative error minimum sum of squares. $F(E)$ is relative error minimum sum of squares.

$\left[\frac{\mathrm{d}a}{\mathrm{d}N}(E)\right]_i$ is the calculated value of CFCP at *i*th experimental data point under polarization potential *E*. $\left[\frac{\mathrm{d}a}{\mathrm{d}N}(E)\right]_i^s$ is the measured value of CFCP at *i*th experimental data point under polarization potential *E*. *p* is the total number of test points under polarization potential *E*.

According the method above, the optimal $C(E)$ at various polarization potentials was shown in Table.2.

Table 1. The $\frac{\mathrm{d}a}{\mathrm{d}N}$ ～ΔK formulae of 38CrSi in 3.5% NaCl solution by various polarization potentials

Media	E, mV	$\frac{\mathrm{d}a}{\mathrm{d}N}$
air		$6.2045\times10^{-8}\times(\Delta K)^{2.1229}$
3.5%NaCl	-200	$3.2048\times10^{-7}\times(\Delta K)^{1.9633}$
3.5%NaCl	-300	$2.8019\times10^{-7}\times(\Delta K)^{2.0017}$
3.5%NaCl	-400	$1.1997\times10^{-7}\times(\Delta K)^{2.2049}$
3.5%NaCl	-800	$1.1601\times10^{-7}\times(\Delta K)^{2.1982}$
3.5%NaCl	-900	$1.3987\times10^{-7}\times(\Delta K)^{2.1498}$
3.5%NaCl	-1000	$1.1389\times10^{-7}\times(\Delta K)^{2.2043}$
3.5%NaCl	-1050	$2.0121\times10^{-7}\times(\Delta K)^{2.2033}$
3.5%NaCl	-1100	$2.0295\times10^{-7}\times(\Delta K)^{2.0802}$
3.5%NaCl	-1200	$1.3992\times10^{-7}\times(\Delta K)^{2.1609}$

Table 2. Optimum $C(E)$ values of 38CrSi in 3.5% NaCl solution by various polarization potentials

E,mV	-200	-300	-400	-800	-900	-1000	-1050	-1100	-1200
C(E)	1.823	1.621	1.483	1.299	1.301	1.078	1.406	1.641	1.698

If $E\geq$-1000mV, $C(E)=0.00078E+1.7997$; If $E<$-1000mV， $C(E)=0.0001E+1.5040$.

3.2.3 Establishment of corrosion fatigue crack propagation model

Taking corrosion accelerated factor and formula (4) into formula (7) and (4), the corrosion fatigue crack propagation model was got, which was shown below.

If $E \geq -1000$mV， $$\frac{\mathrm{d}a}{\mathrm{d}N}(E)=[0.00078E+1.7997]\times 6.2045\times 10^{-8}\times(\Delta K)^{2.1344} \quad （8）$$

IF $E <-1000$mV 时， $$\frac{\mathrm{d}a}{\mathrm{d}N}(E)=[-0.0001E+1.5040]\times 6.2045\times 10^{-8}\times(\Delta K)^{2.1344} \quad （9）$$

The unit of $\frac{\mathrm{d}a}{\mathrm{d}N}(E)$ is mm/cycle. The unit of stress intense factor is MPa·m$^{1/2}$.The unit of polarization potential E is mV.

In order to fulfill engineering precision requirement， $\overline{\delta(E)}$ should be less than 10% and $[\delta(E)]$ less than 20%.$[\delta(E)]$ is relative error between calculated CFCP rate and test results. $\overline{\delta(E)}$ is the average of $[\delta(E)]$.

$$[\delta(E)]_i=\left|\frac{\left[\frac{da}{dN}(E)\right]_i-\left[\frac{da}{dN}(E)\right]_i^s}{\left[\frac{da}{dN}(E)\right]_i^s}\right|\times 100\% \quad （10）$$

$[\delta(E)]_i$ is relative error between calculated CFCP rate and test result at the *i*th test point. $\left[\frac{da}{dN}(E)\right]_i$ is CFCP rate from calculation. $\left[\frac{da}{dN}(E)\right]_i^s$ is CFCP rate from test.

The calculation results of relative error at various corrosion fatigue crack propagation $[\delta(E)]_{\max}$ and relative average error were shown in Table.3.

Table 3. $[\delta(E)]_{\max}$ and $\overline{\delta(E)}$ by various polarization potentials

E,mV	-200	-300	-400	-800	-900	-1000	-1050	-1100	-1200
$[\delta(E)]_{\max}$	13.2	11.5	10.9	13.1	17.1	16.5	11.9	13.2	12.1
$\overline{\delta(E)}$	5.11	3.6	4.10	4.79	8.63	6.25	5.13	5.23	4.73

Table 3 shows that $[\delta(E)]_{\max}$<20% and $\overline{\delta(E)}$<10%.

4. CONCLUSIONS

Although a lot of investigations on steel corrosion fatigue were performed [14-17], there are different behaviors for variation steel types. The study in the paper got a detail investigation for 38CrSi corrosion fatigue crack propagation behavior, which is important for amphibious vehicular designation. Fatigue crack propagation life decreases at cathode polarization with polarization potential moving toward positive direction. Fatigue crack propagation life increase at anodic polarization. With polarization potential moving toward negative directions, it increases more. When polarization potential is below -1000mV, fatigue crack propagation rate decreases. The relationship for 38CrSi steel between fatigue crack propagation life and polarization potential in 3.5% NaCl solution was got. The corrosive fatigue crack propagation model $\frac{\mathrm{d}a}{\mathrm{d}N}(E)\sim$（$\Delta K$，$E$）is established.

References

1. G.W.Song, Y.B.Huang,*Corrosion & Protection*,32 (2011)646-668
2. R.E.Melchers.*Corros.Sco*.,48(2006)4174-4180
3. Z.B.Wang,Q.Song.*Iron&Steel*,36(2001)66-78
4. X.G.Li,*World Sci-tech R&D*,4(2001)11-17
5. Z.G.Ma,L.B.Ren,*Handbook of modern engineering materials*,China Astronautic Publishing House,Beijing(1992)
6. Z.G.Jiang,*Aircraft structure corrosion fatigue*, Aviation Industry Press,Beijing(1992)
7. J.Billingham, J.V.Sharp,*Review of the Performance of high strength steels used offshore*.UK:Health and Safety Executive(2003)
8. O.Vosikovsky, *J. Test. EVAl*, 6(1978)175
9. Z.Y.Xu, *J.Southwest Petroleum Institute*,12(1990)84-91
10. R.N.Parkins,*Met.Sci*,13(1979)381
11. W.Hooper,W.H.Hartt,*Corrosion*,34(1978)320
12. N.J.Wadsworth.*Internal Stress and Fatigue in Metals*.Elsevier,Amsterdam(1959)
13. H.L.Marcus.*Corrosion Fatigue Mechanics,Metallurgy,Electrochemistry and Engineering*.American Society for Testing&Material(1983)
14. H.B.Gao,Acta Metallurgica Sinica.27(1991)205-270
15. Y.N. Xue, J.L Xu, Y.P.Li&H.Li,*China Ocean Engineering*,7(1993)139-146
16. J.Liang, *J. Mechanical Strength*,26(2004)74-76
17. M.Y.Pan,P.Z.Zhang,H.C.Zhang,*Corrosion Science&Protection Technology*,10(1998)316-320