Study on the galvanic corrosion phenomenon of cladding steel bars

Jian ping Tan 1*, Zheng Yang 2 and Zhen Li3

1 Intelligent measurement and control laboratory, Central South University, Chang Sha, Hu Nan, 410012, China
2 Intelligent measurement and control laboratory, Central South University, Chang Sha, Hu Nan, 410012, China
3 Intelligent measurement and control laboratory, Central South University, Chang Sha, Hu Nan, 410012, China

*Corresponding author’s e-mail: jptan@163.com

Abstract. To explore corrosion law of bimetallic interface of a new type of steel bars, which cladded in stainless steel by hot rolling process, COMSOL Multiphysics electrochemical corrosion module, as a simulation tool, was used for studying the electrode potential distribution, current density distribution and electrode surface morphology change during the corrosion process at the reinforced bimetal bonding surface of cladding layer combining with the surface of the electrode potential distribution in the process of corrosion, the current density distribution and the electrode surface morphology change in bimetallic interface of our new type steel bars, at the same time use the salt fog corrosion, equipment corrosion test was carried out on the cladding steel, used to verify the accuracy of the simulation results. The results suggested that the coating electrode potential of stainless steel was obviously higher than that of carbon steel, in combination with surface constitute a pair of electrodes, the increased incidence of corrosion of carbon steel side and in the simulation and experiment are form a "V" corrosion pits, by measuring found that, in the condition of the mass fraction of 5% salt spray and 50 ℃ temperature, average surface cladding steel corrosion rate is 2.2 * 10^(-3) mm/h.

1. Introduction

The failure of concrete structure buildings is usually caused by the corrosion of internal steel reinforcement, especially in the highly corrosive environment such as Marine engineering, the actual service life of concrete buildings is often lower than its design life, mainly because of the rapid corrosion of steel reinforcement in the high-concentration Cl- environment [1], including hot rolled stainless steel, carbon steel cladding steel show good comprehensive mechanical properties and corrosion resistance, is expected to realize industrialization production[2-6]. During the production of hot-rolled coated steel bar, the stainless steel tube is nested on the carbon steel round billet through a specific billet forming process, and then the high temperature rolling method is used to achieve the metallurgical combination between the outer stainless steel and the inner carbon steel, so that the corrosion resistance of the steel bar is close to that of pure stainless steel bar, and the cost is lower than that of pure stainless steel bar [7]. Hot rolled stainless steel, carbon steel cladding steel can greatly improve the corrosion resistance of steel, but when the outer stainless steel, the inner carbon steel exposed in strong corrosive environment when bimetal interface will constitute the electrochemical reaction, accelerate the corrosion of carbon
steel dissolved, double metal layered or shedding of stainless steel cladding, lead to reinforced early failure, reduce the service life.

In the electrochemical corrosion study of stainless steel and carbon steel, Kaibin Nie et al. [8] studied the galvanic corrosion phenomenon of stainless steel coated steel in red soil by weight-loss method and electrochemical method, and the research results showed that the galvanic corrosion accelerated the corrosion of carbon steel as the anode. Zhuanchang Wang et al. [9] studied the electrochemical corrosion phenomenon and mechanism of N80 carbon steel and 13Cr stainless steel using weight-loss method, in-situ electrochemical measurement and surface analysis technology, and obtained the sequence of corrosion effects of three corrosion inhibitors on the electrochemical corrosion of N80 carbon steel and 13Cr stainless steel.

Finite element simulation can effectively replace or assist the actual corrosion test when studying the electrochemical corrosion of stainless steel and carbon steel. Rachid Radouani et al. [11] studied the galvanic corrosion of carbon steel end plate and low alloy steel bolts in 1m hydrochloric acid solution by means of electrochemical method. They numerically simulated the corrosion parameters of joint parts by using COMSOL Multiphysics software, and analyzed the galvanic corrosion phenomenon of the contact area between head bolts and end plate. It is found that the corrosion rate is higher in the contact area between bolt head and endplate, and lower in other areas. Xu dong Cheng [12] et al used COMSOL Multiphysics software to simulate the difference in the corrosion process between circular and ribbed steel bars in concrete structures after chloride ion deobtuse. The results showed that: in two kinds of steel bars of the same specification and under the same working condition, ribbed steel bars had shorter depassivation time, preferred corrosion and higher corrosion rate than circular steel bars.

Based on the CMSOL Multiphysics finite element multi-physical field coupling simulation software, this paper analyzed the information such as the change of morphology, electrode potential distribution, corrosion depth, when the galvanic corrosion accelerated at the steel bimetal interface of stainless steel-carbon steel cladding reinforcement.

2. COMSOL corrosion simulation of cladding reinforcement

2.1. Cladding reinforcement material and corrosive medium
The main components of cladding reinforcement and carbon steel core used in this study are shown in Table 1 [12][13]:

| Elements | Stainless steel coating | Carbon steel core |
|----------|-------------------------|-------------------|
| C        | ≤0.08                   | 0.5 ± 0.02        |
| Si       | ≤1.00                   | 0.4 ± 0.05        |
| Mn       | ≤2.00                   | 1.0 ± 0.06        |
| P        | ≤0.045                  | 0.1 ± 0.01        |
| S        | ≤0.030                  | 0.1 ± 0.01        |
| Cr       | 16.00~18.50             | 1.5 ± 0.05        |
| Ni       | 10.00~14.00             | 1.00 ± 0.05       |
| N        | 2.00~3.00               | 0.015 ± 0.005     |
| V        | 0.2 ± 0.01              |                   |

Divide the elements in the table by Fe.

2.2. Physical Model
FIG. 1 is a schematic diagram of two-dimensional simulation model. The etchant surface selected is the interface between stainless steel and carbon steel bimetal and the adjacent area, where the coating thickness is 1.0mm, which is consistent with the actual 25 coating thickness of reinforcement. Figure 2 is a schematic diagram of grid division. The grid type is fluid dynamics. The reaction mainly occurs at
the interface between two electrodes and corrosive medium, so the grid is predefined as "extremely refined" and the other areas as 'relatively refined'. Formatting author affiliations

2.3. Driving equation

The transfer of substance I in electrolyte can be described by the Nernst-Plank equation:

$$\frac{\partial c_i}{\partial t} = -\nabla N_i = D_i \nabla^2 c_i - z_i F u_i \nabla (c_i \nabla \phi) + \nabla c_i V$$  \hspace{1cm} (1)

In the formula, $C_i$ is the concentration of I ions (mol/m$^3$), $N_i$ is the flux of I ions (mol.m$^{-2}$.s$^{-1}$), $D_i$ is the diffusion coefficient of I ions (m$^2$/s), and $Z_i$ is the charge number of I ions. $F$ is Faraday constant.
(C/mol), $U_I$ is the mobility of I ions (M·s⁻¹·v⁻¹), is the electrolyte potential (V), $V$ is the convection rate (m/s).

2.4. Simulation parameter setting

The main parameters of simulation are set as shown in Table 2.

| Name      | Numerical value          |
|-----------|--------------------------|
| $E_{eq\_cat}$ | -0.58[V]               |
| $E_{eq\_an}$  | -1.49[V]                |
| $\rho_{Fe}$   | 7874[kg/m³]             |
| $M_{Fe}$      | 0.056[kg/mol]           |
| $k_{sp}$      | $2\times10^{-5}$[mol³/m⁹] |
| Temperature  | 50°C                    |
| Time         | 480h                    |

The contents of the table are as follows: anode stainless steel self-etching potential, cathode carbon steel self-etching potential, cathode density, cathode molar mass, corrosion product deposition coefficient, temperature and total reaction time.

2.5. Analysis of simulation results

The corrosion process and results of cladding reinforcement with defects under neutral salt spray environment were simulated by using the subscale corrosion in the galvanic couple corrosion module in COMSOL Multiphysics. Figure 3-6 shows the simulation results.
From the figure 3, stainless steel as cathode, electrode potential significantly below as anode carbon steel, surface area and the greater the rate of change of electrode potential difference, it is easier to
produce electrochemical reaction, thus combining surface corrosion at the start are more likely to happen, and further accelerate the corrosion of corrosion pit pit corrosion, and formed a "V" corrosion pit.

It can be seen from Figure 4 that the current density in the "deep V-shaped" corrosion pits gradually increases from top to bottom and reaches its maximum value at the bottom, indicating that the low electrochemical reaction rate of corrosion pits always reaches its maximum value, which also explains the formation of the clothing pit morphology.

Can be seen from the figure 5, as the reaction progresses, the face of the current density change is bigger and bigger, and the "V" corrosion pit is the maximum current density change, small electrode gap reduced the electrolyte ion transport in time, increase the ion transfer rate, forming a similar the types of corrosion, crevice corrosion speed up the development along the joint surface corrosion.

Figure 6 for reaction electrode shape and corrosion products eventually Fe (OH) 3, Fe (OH) 2 sedimentary images, such as tallies with the actual salt fog corrosion results and the accuracy of the simulation result is verified by different corrosion depth measurement after corrosion simulation found that corrosion depth $d$ (mm) with time $t$ (h) is roughly linearly related (as shown in figure 7), is about the relation between the $d = 2.2 \times 10^{-3}t$.

![Figure 7 Corrosion depth/time diagram](image)

3. Neutral salt spray corrosion test for cladding reinforcement

3.1. Setting of test parameters
In order to quickly observe the corrosion development process of cladding reinforcement joint surface in the simulated Marine environment with high concentration of Cl-, the neutral salt spray accelerated corrosion test was selected. The test conditions were as follows: NaCl salt spray with a mass fraction of 5%, a temperature of 50°C, a PH of 6.5~7.2, and a total test duration of 20 days. The samples are 25 diameter cladding reinforcement, with an average thickness of 1mm and a length of 250mm. Each sample has three artificial defects of 12mm × 3mm × 5mm (length × width × depth) uniformly distributed on the surface.

3.2. Analysis of test results
After the completion of the experiment, the sample is shown in FIG. 8. It can be seen that the cladding reinforcement has relatively serious corrosion at the end face and reserved defects, while the corrosion on other surfaces is not obvious.
The corroded samples were made into metallographic samples, and the corrosion depth of the bimetal bonding surface under the actual salt spray corrosion was observed and measured with a metallographic microscope. The microscopic image of the samples was shown in FIG. 9, indicating that many groups of samples were "deep V-shaped" corrosion pits. Statistics show that the average corrosion depth of the bonding surface is 1.06mm (20 days), which is consistent with the simulation results.

4. Conclusion
(1) Compared with the actual salt spray corrosion test, COMSOL Multiphysics can effectively simulate the galvanic couple corrosion of cladding reinforcement under the set conditions, and characterize the corrosion changes at the joint surface.

(2) According to the test and simulation, the galvanic corrosion at the bonding surface accelerates the corrosion of the bonding surface and forms a "deep V-shaped" corrosion pit. The further development of corrosion may lead to the damage or fall off of the cladding layer and reduce the service life of the cladding reinforcement.

(3) Under the condition of neutral salt spray with a mass fraction of 5% and a temperature of 50℃, the average corrosion rate of the cladding reinforcement bonding surface was found to be $2.2 \times 10^{-3}\text{mm/h}$, which was consistent with the simulation results and verified the accuracy of the simulation results.
References

[1] Liyuan Song. Study on chloride ion corrosion durability of marine reinforced concrete structures [D]. Liaoning: Dalian University of Technology, 2009. DOI:10.7666/D.Y1602228.

[2] Dongming Yan, Zhihao Huang, Gong Chen, et al. Experimental study on corrosion resistance of rebar with low temperature sintered active enamel coating [J]. Journal of zhejiang university (engineering science), 2020, 54(1): 56-63. DOI:10.3785/j.issn.1008-973x.2020.01.007.

[3] Zhan Guo, Weiguo Wan, Wei Sun, etc. With the research of rare earth high strength and corrosion resistant steel [J]. Journal of iron and steel, 2010, (12) : 53-58.

[4] Kunming University of Science and Technology. A method for preparing protective reinforcement for corrosion-resistant construction: CN201910492394.x [P]. 2019-07-26.

[5] Zhi Yong. Ai, Jin Yang. Jiang, Sun. Wei, et al. Passive Behaviour of New Alloy Corrosion Resistant Steel Cr10Mo1 in Simulating Concrete Pore Solutions with Different Chloride Contents[J]. Key Engineering Materials, 2016, 4199(1422): 1053-1060. DOI:10.4028/scientific.net/KEM.711.1053.

[6] Sami Masadeh. Performance of Galvanized Steel Reinforcement in Concrete in Sea and Dead Sea Water[J]. Journal of Materials Science and Chemical Engineering, 2015, 3(05): 46-53. DOI:10.4236/msce.2015.35006.

[7] Yong Xiang, Ling Huang, Linfang Zeng, et al. Application prospect of high strength stainless steel clad steel reinforcement in bridge and tunnel engineering [C]// Chinese Academy of Engineering, Chinese Society of Civil Engineering, Shanghai Association of Science and Technology, Shanghai Society of Civil Engineering. 2019 (8th) International Bridge and Tunnel Technology Conference proceedings.

[8] Hunan Santai New Material Co., LTD. A Corrosion-resistant titanium steel composite reinforcement and its preparation method: CN201910461188.2[P]. 2019-08-30.

[9] Nie kaibin, yan aijun, yao yao, et al. Corrosion behavior of stainless steel coated steel in red soil [J]. Corrosion and protection, 2016, 37(8): 639-643. DOI:10.11973/fsyfh-201608007.

[10] Wang, Z. Z., Zhang, G. A., Li, Y. Y.. Inhibitive effects of inhibitors on the galvanic corrosion between N80 carbon steel and 13Cr stainless steel under dynamic supercritical CO2 conditions[J]. Corrosion Science: The Journal on Environmental Degradation of Materials and its Control, 2019, 146(Jan.): 121-133.

[11] Rachid Radouani, Younes Echcharqy, Mohamed Essahli. Numerical Simulation of Galvanic Corrosion between Carbon Steel and Low Alloy Steel in a Bolted Joint[J]. International journal of corrosion, 2017, 2017: 6174904.1-6174904.10.

[12] Xudong Cheng, Li Xu, Yanping Fan, et al. Corrosion behavior of alien reinforcement under chloride ion erosion [J]. Corrosion and protection, 2016, 37(5): 407-413. DOI:10.11973/fsyfh-201605013.

[13] State Administration for Market Regulation, Standardization Administration of China. Hot-rolled carbon steel-stainless steel composite reinforcement for reinforced concrete :GB/T 36707-2018[S].

[14] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of China. Permissible deviation of chemical composition of Steel Products: GB/T 222-2006[S], 2006.