Study on Electrochemical Corrosion Rate of Braided Wire Rope

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Abstract. Taking 8×19 traction galvanized Braided steel wire rope as the research object, we carried out the electrochemical corrosion test of the steel wire rope matrix and the galvanized layer. And the response surface method was used to examine the influence of the interaction of three factors on the corrosion rate of steel wire rope. The results show that the corrosion rate of the braided steel wire rope matrix and the galvanized layer increases with the increase of temperature and the decrease of pH value, and increases first and then decreases with the increase of Cl- concentration. There is a nonlinear relationship between corrosion rate and temperature, Cl- concentration and pH value. In the same corrosive environment, the corrosion rate of the galvanized layer of the wire rope is greater than the corrosion rate of the matrix. The influence degree of the three factors on the corrosion rate of the steel wire rope matrix and the galvanized layer under the interaction is: pH>temperature>Cl- concentration.

1. Introduction
Braided steel wire rope is an important part of Tension stringing Engineering. Its reliability is related to the normal operation of the stringing construction and the safety of the construction personnel. The service environment of braided steel wire rope is varied, and it often works in open air environment. The corrosive substances in atmosphere are also different under different environment. The CO₂ and SO₂ discharged from industrial production in the industrial environment will make the atmosphere acidic, the higher Cl- content in the atmosphere of coastal areas, and the harmful ions adsorbed on the surface of steel wire rope in high temperature and rainy atmosphere in summer will cause electrochemical corrosion on the surface of steel wire rope. The corrosion pit is formed on the surface to reduce the cross section area of the steel wire rope and reduce the load capacity of the wire rope. When the galvanized layer on the surface of the steel wire rope is corroded, the steel wire rope matrix will also be exposed to electrochemical corrosion in the corrosive environment.

In recent years, domestic and foreign scholars have done a lot of research on the corrosion mechanism and corrosion rate of steel wire: Chen Xiaoyu[1] elaborated on the mechanism of temperature, humidity and atmospheric pollutants affecting the corrosion of the main cable wire of the suspension bridge and its influence on the corrosion rate. B. Daz et al. [2] studied the effect of temperature, Cl-, oxygen on the electrochemical corrosion behavior of cold-drawn steel wire by cyclic voltammetry and impedance spectroscopy. The results showed that Cl-, the utilization of oxygen and the change of temperature were important factors for the corrosion of steel wire. Wang Songquan et al. [3] took the mine hoisting wire rope as the research object, and measured the polarization curves of steel wires with different surface treatments under different corrosion environments on the electrochemical workstation. The analysis results show that the corrosion environment and the surface treatments of steel wires have a great influence on the corrosion rate of steel wires. Li Xueming et al.
[4] studied the effect of temperature on the corrosion behavior of bridge cable galvanized steel wire in simulated acid rain solution. The results show that the corrosion rate of galvanized steel wire increases with the increase of temperature. Tan Tian et al. [5] studied the electrochemical corrosion behavior of galvanized layer on transmission tower in simulated marine and industrial environment by polarization curve method. The results showed that the corrosion rate of galvanized layer was proportional to the concentration of NaCl and NaHSO₃ mixed solution. Wang et al. [6] used orthogonal corrosion test to study the polarization curves of mining steel wires with different surface treatment methods and different soaking media. The research shows that the steel wire is more corrosive in acidic environment than in alkaline environment. Miao Changqing et al. [7] used orthogonal test design method to study the effects of temperature, Cl⁻ concentration, pH value and the interaction of the three on the corrosion rate of steel wire.

In this paper, 8×19 traction galvanized Braided steel wire rope was taken as the research object. The electrochemical corrosion process was modeled in the laboratory, and experimental study on corrosion rates of strands with and without galvanized layer in different corrosive environments. At the same time, the effects of various factors on the corrosion rate of the braided steel wire rope matrix and the galvanized layer were investigated.

2. Test
Taking 8×19 traction galvanized Braided steel wire rope as the research object, we made two strands to make the working electrode with galvanized layer and galvanized layer removed. The length of the strands exposed to corrosion environment was 2 cm and the corrosion surface area was 1.88 cm². The working electrodes were cleaned by ultrasonic wave in anhydrous ethanol for 15 minutes before testing.

Polarization curve testing was performed on CHI604E electrochemical workstation. The electrolytic cell uses a three-electrode system, the sample is a working electrode, the platinum plate is an auxiliary electrode, and the saturated calomel electrode is a reference electrode. The scanning speed was 10 mV/s, and the scanning interval was ±400 mV from the corrosion potential of the sample (relative to the saturated calomel electrode). The test method selects the Tafel polarization curve method.

The influence of single factor (temperature, Cl⁻ concentration, pH value) and multi-factor (interaction) on the corrosion rate of braided wire rope was studied according to the working conditions of braided wire rope. The Box-Behnken design of response surface methodology was used in the multi-factor interactive test. The temperature of the test was controlled by a thermostat, the concentration of Cl⁻ was controlled by the content of NaCl in the solution, and the pH was configured with concentrated sulfuric acid and pure water. The corresponding corrosion rate is obtained by Tafel linear extrapolation. When studying the influence of single factor on the corrosion rate of braided steel wire rope, if there is no special explanation, the temperature is 25 °C, ρ(Cl⁻)=0%, and pH=7. The corresponding corrosion rate is obtained by Tafel linear extrapolation. The experimental data is fitted by exponential function, logarithmic function, power function, linear function and polynomial respectively. The maximum function of fitting the correlation coefficient square is taken as its fitting regression equation.

3. Result and discussion

3.1 Corrosion rate of steel wire rope matrix and galvanized layer under single factor
Figures 1(a) and 3(a) show that the polarization curves of the steel wire rope matrix and galvanized layer at different temperatures. From the graphs, it can be seen that the polarization curves of the steel wire rope matrix and galvanized layer move to the upper right with the increase of temperature, and the self-corrosion potential decreases. Figures 2(a) and 4(a) are the fitting curves of corrosion rate of steel wire rope matrix and galvanized layer at different temperatures. The regression equations are

\[ R_1=0.0127e^{0.0498x}, \quad R_2=0.9924, \quad R_3=0.0196e^{0.0491x}, \quad R_4=0.9738, \]

respectively. It can be seen from the
figure that the corrosion rate of the steel wire rope matrix and the galvanized layer increases with the increase of temperature. The main reason for the analysis is that the cathode mainly undergoes oxygen absorption corrosion in the environment, and the temperature rise will increase the oxygen diffusion coefficient in the solution, thereby accelerating the corrosion process.

Figures 1(b) and 3(b) show that the polarization curves of the steel wire rope matrix and galvanized layer at different Cl\(^-\) concentration. It can be seen from the graph that the polarization curves of the steel wire rope matrix and galvanized layer move first to the upper right with the increase of Cl\(^-\) concentration, and the self-corrosion potential decreases. The polarization curve moves to the lower left side and the self-corrosion potential increases when the concentration of Cl\(^-\) is greater than 3\%. Figures 2(b) and 4(b) are fitting curves of corrosion rate of steel wire rope matrix and galvanized layer at different Cl\(^-\) concentration. The regression equations are \(R_1=0.0227x^2+0.1582x+0.0252\), \(R_2^1=0.9521\), \(R_2=0.0325x^2+0.2388x+0.0244\), \(R_2^2=0.9386\) respectively. The results show that the corrosion rate of steel wire rope matrix and galvanized layer increases first and then decreases with the increase of Cl\(^-\) concentration in solution. The main reason is that oxygen absorption corrosion of steel wire rope matrix occurs mainly in Cl\(^-\) solution, and the oxygen content and Cl\(^-\) concentration in solution will affect the corrosion rate. When the concentration of Cl\(^-\) is less than 3\%, the concentration of Cl\(^-\) plays a leading role in the corrosion rate. Cl\(^-\) forms FeCl\(_2\) by binding with Fe\(^{2+}\) in the surface active region of the matrix, and then hydrolyzes to produce HCl, which reduces the pH value of the solution and promotes the dissolution of the steel wire rope matrix. When the Cl\(^-\) concentration is more than 3\%, the dissolved oxygen content decreases with the increase of Cl\(^-\) concentration, the oxygen consumption of anodic reaction decreases, and the corrosion rate decreases. At this time, the dissolved oxygen content plays a leading role in the corrosion rate of the steel wire rope matrix. For the galvanized layer, when the Cl\(^-\) concentration is less than 3\%, the Zn\(^{2+}\) produced by the anode hydrolyze to form Zn(OH)\(_2\) or ZnO, and the Zn\(^{2+}\) in the Zn(OH)\(_2\) combine with the chlorine in the solution to form soluble salts, which reduces the surface protection of the galvanized layer. With the increase of Cl\(^-\) concentration, the speed of this transformation will be faster, thus accelerating the corrosion of galvanized layer. The corrosion products of the galvanized layer are mainly insoluble Zn\(_n\)(OH)\(_{6n}\)Cl\(_2\)•H\(_2\)O when the concentration of Cl\(^-\) is more than 3\%, which reduces the corrosion rate of the galvanized layer.

Figures 1(c) and 3(c) show that the polarization curves of steel wire rope matrix and galvanized layer at different pH values. From the graph, it can be seen that the polarization curves of steel wire rope matrix and galvanized layer move to the upper right with the decrease of pH value, and the self-corrosion potential decreases. Figures 2(c) and 4(c) are fitted curves of corrosion rate of steel wire rope matrix and galvanized layer at different pH values. The regression equations are \(R_1=7.3415x-2.574\), \(R_2^1=0.9899\), \(R_2=11.981x^{-2.562}\), \(R_2^2=0.9804\), respectively. It is shown from the graph that the corrosion rate of steel wire rope matrix and galvanized layer increases with the decrease of pH value. The main reason is that hydrogen evolution corrosion mainly occurs in cathode in acidic environment. With the decrease of pH value, the increase of H\(^+\) concentration in solution accelerates the corrosion process.

![Figure 1. Polarization curve of the steel wire rope under single factor.](image)
Figure 2. Corrosion rate fitting curve of steel wire rope under single factor.
(a) different temperatures  (b) different Cl⁻ concentrations   (c) different pH values

Figure 3. Polarization curve of galvanized layer of wire rope under single factor.
(a) different temperatures   (b) different Cl⁻ concentrations   (c) different pH values

Figure 4. Corrosion rate fitting curve of steel wire galvanized layer under single factor.
(a) different temperatures   (b) different Cl⁻ concentrations   (c) different pH values

3.2. Corrosion rate of steel wire rope matrix and galvanized layer under multifactor interaction

3.2.1. Response surface design and test results verification
Response surface design and test results are shown in table 1. Among them, R₁ is the corrosion rate of the braided wire rope matrix and R₂ is the corrosion rate of the galvanized layer of the braided wire rope.

| Run | A (℃) | B (Cl⁻ %) | C (pH) | R₁ (mm/a) | R₂ (mm/a) |
|-----|-------|-----------|--------|-----------|-----------|
| 1   | 20    | 4         | 2      | 5.332     | 8.446     |
| 2   | 60    | 6         | 4      | 0.437     | 0.663     |
| 3   | 40    | 6         | 6      | 0.196     | 0.273     |
| 4   | 40    | 6         | 2      | 9.842     | 14.94     |
| 5   | 20    | 4         | 6      | 0.139     | 0.202     |
| 6   | 20    | 6         | 4      | 0.258     | 0.359     |
| 7   | 40    | 4         | 4      | 0.29      | 0.461     |
Response surface function equations between A, B, C and corrosion rate R of braided wire rope matrix and galvanized layer were established respectively by using complete quadratic polynomial regression.

\[ R_1 = 0.29 + 2.26A - 0.24B - 6.03C - 0.041AB - 4.23AC + 0.42BC + 0.87A^2 - 0.79B^2 + 5.97C^2; \]
\[ R_2 = 0.46 + 3.09A - 0.36B - 8.95C - 0.062AB - 5.81AC + 0.64BC + 1.05A^2 - 0.96B^2 + 8.78C^2. \]

Formula: A is temperature, B is Cl\(^{-}\) concentration, C is pH value.

3.2.2. analysis of test results

Figure 5. Three-dimensional diagram of corrosion rate of matrix under multiple factors
(a) pH=3  (b) Cl\(^{-}\) =2%  (c) T=30\(^\circ\)C

Figure 6. Three-dimensional diagram of corrosion rate of galvanized layer under multiple factors
(a) pH=3  (b) Cl\(^{-}\) =2%  (c) T=30\(^\circ\)C

Analysis of Figure 5 and Figure 6 shows that the corrosion rate of the galvanized layer of the steel wire rope is greater than the corrosion rate of the matrix in same corrosive environment. The influence of three factors on the corrosion rate of the steel wire rope matrix and the galvanized layer is: pH>temperature>Cl\(^{-}\) concentration.
4. Conclusion

(1) The corrosion rate of the braided steel wire rope base and the galvanized layer is significantly affected by temperature, Cl\(^{-}\) concentration and pH value. It increases with the increase of temperature and the decrease of pH value, and increases first and then decreases with the increase of Cl\(^{-}\) concentration. There is a nonlinear relationship between corrosion rate and temperature, Cl\(^{-}\) concentration, and pH.

(2) With the change of temperature, Cl\(^{-}\) concentration and pH value, the corrosion rate of the galvanized layer and the matrix of the braided steel wire rope changed substantially the same. However, in the same corrosive environment, the corrosion rate of the galvanized layer of the steel wire rope is greater than the corrosion rate of the matrix.

(3) The effect of temperature, Cl\(^{-}\) concentration, and pH on the corrosion rate of braided steel wire rope is not a simple linear superposition, but an interaction. The influence of three factors on the corrosion rate of the steel wire rope matrix and the galvanized layer is: pH>temperature>Cl\(^{-}\) concentration.

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