The Investigation of Corrosion Property of The Four Coatings in The Transformer Substation Soil

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Abstract: Pure Al coating, AlSi alloy coating, NiAl alloy coating and 316L stainless steel coating were prepared on the Q235 steel by arc spraying technology. The corrosion of the four sprayed alloy coatings in the 220kV transformer substation soil and soil solution was studied by buried specimens and electrochemical test in Hunan. The corrosion behaviors of the coating steel samples in transformer substation soil solution were investigated by line polarization, potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) tests. The results show that the best corrosion resistance of the four sprayed alloy coatings was AlSi coating, sequentially in the order of NiAl and stainless steel coating, and the Al coating was easy bouffant at long time in the underground, so that the corrosion resistance is not good.

1. Introduction
Grounding grid is an important facility to ensure the safe and stable operation of power equipment in the substation, which is usually buried in 60-80 centimeters under the ground of substation. Hot dip galvanized carbon steel is the main material for grounding grid in China. However, the corrosion of power grounding grid is serious, especially in South and Central China, severe corrosion of galvanized steel occurred after 3-5 years, resulting in many equipment damage and power failure accidents [1-2]. Thermal spraying has been widely used in metal anti-corrosion, such as hot spraying zinc, zinc and aluminum alloy, which has excellent atmospheric corrosion resistance and is mainly used in highway, bridge, outdoor frame and other anti-corrosion [3-6]. However, there are few studies on the application of thermal spraying alloy coatings in grounding grid anti-corrosion. Theoretically, thermal spraying alloy coatings have both anti-corrosion, conductivity, thermal stability are potential corrosion protection methods for grounding grids and have good application value. Al, NiAl, AlSi and 316L stainless steel coatings were prepared on the surface of Q235 steel by high-speed arc spraying. The corrosion resistance of the four coatings in substation soil and its solution was studied by electrochemical experiments in substation buried samples and soil solution, so as to improve the corrosion resistance of grounding grid.

2. Experimental
This experiment adopts JP5000 supersonic flame spraying equipment. Using Q235 steel as substrate, four kinds of alloy coatings of Al, AlSi, NiAl and 316L stainless steel were prepared at the same time after cleaning and degreasing with alcohol, then sandblasting and coarsening, then fixing the substrate to 200°C, then spraying on six surfaces. The electrochemical measurements were carried out at room temperature by Garmy 600 electrochemical workstation. The test solution was soil filtrate of a 220 kV
substation in Hunan Province in China. The water-soil ratio was 3:1. The physical and chemical parameters of soil solution were determined. As shown in Table 1, the substation has a high degree of soil acidity, high chloride ion and sulfate ion content, and strong corrosiveness. For comparison, Q235 steel and SPA-H weathering steel were also tested. Their compositions are shown in Table 2.

Table 1 The parameter of the soil solution for the 220kV transformer substation in Hunan (water: soil=3:1)

|       | Na⁺ | NH₄⁺ | Mg²⁺ | Ca²⁺ | Cl⁻ | F⁻ | NO₃⁻ | SO₄²⁻ | pH | Conductivity cm/s |
|-------|-----|------|------|------|-----|----|------|-------|----|------------------|
| Value | 14.15 | 7.90 | 4.90 | 19.47 | 9.10 | 0.03 | 0.62 | 6.23 | 6.06 | 109.6            |

Table 2 The composition of Q235 steel and SPA-H weathering steel

|       | C   | Si  | Mn  | S   | P   | Cu  | Cr  | Ni  | Fe  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Q235 steel | 0.18 | ≤0.3 | 0.45 | ≤0.05 | ≤0.045 | -   | -   | -   | Bal. |
| SPA-H steel | 0.09 | 0.45 | 0.45 | ≤0.005 | 0.085 | 0.27 | 0.5 | 0.07 | Bal. |

3. Results and Discussion

3.1 Electrochemical Testing

3.1.1 Linear Polarization Measurement

Table 3 is data fitting for linear polarization impedance. The polarization range is -20 mV to 20 mV, and the scanning rate is 0.5 mV/s. According to the linear polarization impedance value, the linear polarization impedance value of AlSi coating is the largest, and its corrosion resistance is the best, followed by NiAl and 316 stainless steel coating, pure Al coating has the worst corrosion resistance, while the corrosion resistance of Q235 steel and SPA-H weathering steel has little difference.

Table 3 The simulated data of the line polarization resistance test

| Sample | Q235 steel | SPA-H steel | Al coating | AlSi coating | NiAl coating | 316L coating |
|--------|------------|-------------|------------|--------------|--------------|--------------|
| Rp (kΩ·cm²) | 15.4 | 13.55 | 12.26 | 266.2 | 158 | 108.8 |

3.1.2 Potentiodynamic Polarization Measurements

Figure 1 shows the potentiodynamic polarization curves of Q235 steel, SPA-H weathering steel and coated samples. The anodic process of all electrodes in the measured solution showed active dissolution characteristics, and there was no obvious passivation potential range. The passivation trend of 316 stainless steel coating was relatively obvious, and the corrosion potential was the highest. Compared with Q235 steel, the anode current density of stainless steel coating is the smallest, followed by NiAl coating and AlSi coating, SPA-H weathering steel is equivalent to Q235 steel, and pure Al coating has the largest anode current density. Table 4 is Icorr and Ecorr for Q235 steel, SPA-H weathering steel and coating samples. Icorr is usually related to corrosion rate. By comparison, Icorr of AlSi coating is the smallest, followed by NiAl and stainless steel coating, Icorr of weathering steel is higher than that of Q235 steel, and Icorr of pure Al coating is the largest. The results of polarization curves are basically consistent with the results of linear polarization. The results show that AlSi coating, NiAl coating and stainless steel coating have better corrosion resistance, while pure Al coating has poor corrosion resistance, and the corrosion resistance of weathering steel is similar to that of Q235 steel.
The result of the potentiodynamic polarization curves test

**Table 4** $I_{corr}$ and $E_{corr}$ for Q235 steel, SPA-H weathering steel and coating samples

| Sample          | Q235 steel | SPA-H steel | Al coating | AlSi coating | NiAl coating | 316L coating |
|-----------------|------------|-------------|------------|--------------|--------------|--------------|
| $E_{corr}$ (mV $_{SCE}$) | -487       | -459        | -848       | -353         | -505         | -254         |
| $I_{corr}$ (μA /cm$^2$)   | 11.6       | 14.5        | 15.4       | 0.396        | 1.09         | 1.41         |

3.1.3 EIS Measurements
Figure 2 is the electrochemical impedance spectroscopy (EIS) measurement of Q235 steel, SPA-H weathering steel and coating samples. Nyquist diagram (Figure 2 (a)) shows that the low frequency capacitive arc resistance of AlSi coating increases significantly, followed by NiAl and stainless steel coating, while the low frequency capacitive arc resistance of pure Al is obviously smaller than that of Q235 steel, and the weathering steel is basically the same as that of Q235 steel. The Bode diagram (Figure 2 (b)) gives the relationship between the impedance modulus $Z$ and the frequency $f$. The larger the $Z$ at $f_0$, the better the corrosion resistance of the electrode. Obviously, the low-frequency $Z$ of Al-Si coating is obviously higher than that of other coatings, and the corrosion resistance is the best, followed by Ni-Al coating and stainless steel coating, both of which are obviously higher than that of Q235 steel. The low frequency $Z$ of pure aluminum coating and weathering steel is equivalent to that of Q235 steel. The relationship between phase angle and frequency (Figure 2 (c)) shows that the impedance spectra of the tested samples show a time constant, and the phase angle of the coated samples moves slightly toward the low frequency direction, especially the stainless steel coating.
According to the shape of impedance spectrum and experience, the equivalent circuit is selected. The impedance spectrum is fitted with the equivalent circuit diagram in Figure 3. $R_{\text{sol}}$ is solution resistance, $C_{\text{dl}}$ is double layer capacitance, $R_{\text{trans}}$ is transfer resistance, $Q_{\text{film}}$ and $R_{\text{film}}$ are film capacitance and resistance. The symbols and curves on Figure 2 are measured and fitted respectively. Table 5 is the fitting parameter of impedance spectrum. AlSi coating has the highest film resistance, followed by NiAl coating and stainless steel coating, which is more than 40 times that of Q235 steel, indicating that the three coatings have better protection to the substrate. The film resistance of pure Al coating and SPA-H weathering steel is slightly higher than that of Q235 steel.

Usually, the corrosion resistance of the sample can be compared simply with the impedance modulus $|Z|_{0.01}$ at low frequency, such as 0.01 Hz. The larger the $|Z|_{0.01}$, the better the corrosion resistance of the sample. Table 6 lists Q235 steel, SPA-H weathering steel and coating sample $|Z|_{0.01}$. 
According to the $|Z|_{0.01}$ value in the table, the impedance of AlSi coating is about 10.5 times higher than that of Q235 steel; the impedance of NiAl coating is about 7.2 times higher than that of Q235 steel; the impedance of stainless steel coating is about 3.3 times higher than that of Q235 steel; and the impedance of weathering steel and pure Al coating is almost the same as that of Q235 steel.

The above impedance measurements are consistent with the linear polarization and potentiodynamic polarization curves. It shows that the AlSi coating has the best corrosion resistance in the soil solution of Maojiatang 220kV substation, followed by NiAl coating and stainless steel coating, while the pure Al coating basically does not have protective property. The SPA-H weathering steel and Q235 steel have the best corrosion resistance. Corrosion resistance is basically the same.

| Sample              | $R_{\text{sol}}$ (Ohm cm$^2$) | $C_{\text{dl}}$ (F cm$^{-2}$) | $R_{\text{trans}}$ (Ohm cm$^2$) | $Q_{\text{film}}$ (F cm$^{-2}$) | $n$ | $R_{\text{film}}$ (Ohm cm$^2$) |
|---------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----|-----------------------------|
| Q235 steel          | 3610                        | 7.38 × 10$^{-10}$           | 4016                        | 0.000274                    | 0.6274 | 4.02 × 10$^2$               |
| SPA-H steel         | 8104                        | 8.42 × 10$^{-9}$            | 1222                        | 0.0003954                   | 0.3911 | 1.16 × 10$^4$               |
| Al coating          | 1536                        | 3.335 × 10$^{-10}$          | 5814                        | 0.0002268                   | 0.1956 | 1.17 × 10$^4$               |
| AlSi coating        | 2598                        | 5.133 × 10$^{-10}$          | 4579                        | 3.01 × 10$^{-5}$            | 0.6066 | 8.58 × 10$^5$               |
| NiAl coating        | 1129                        | 7 × 10$^{-10}$              | 6650                        | 4.17 × 10$^{-5}$            | 0.6731 | 2.7 × 10$^5$                |
| 316L coating        | 2930                        | 8.75 × 10$^{-10}$           | 3729                        | 9.67 × 10$^{-5}$            | 0.5774 | 2.0 × 10$^5$                |

| Table 6 The value of the Q235 steel, SPA-H weathering steel and coating samples, $|Z|_{0.01}$ (Ohm/cm$^2$) |
|-------------------|-----------------------------|
| Sample            | Q235 steel | SPA-H steel | Al coating | AlSi coating | NiAl coating | 316L coating |
|                   |            |            |            |             |              |              |
| $|Z|_{0.01}$        | 12556      | 13283      | 11255      | 131515       | 90240        | 41613        |

3.2 Experiments in Substation
The coated samples were embedded in the 220 kV substation of Maojiatang, Yiyang, Hunan Province. The soil depth of the coated samples was 60 cm. After 180 days of burial, some samples were washed and weighed to calculate the corrosion rate. Table 7 shows that the corrosion rates of the four coatings are obviously lower than those of Q235 steel. AlSi coating has the best corrosion resistance, followed by stainless steel coating, pure Al coating and NiAl coating.

| Table 7 The corrosion rate of buried samples in transformer substation after six months |
|------------------------------------------|-----------------------------|
| Sample        | Q235 steel | SPA-H steel | Al coating | AlSi coating | NiAl coating |
| Corrosion Rate, g/dm$^2$.a                | 0.527        | 0.026       | 0.012      | 0.034        | 0.027        |

4. Conclusion
Electrochemical corrosion behaviors of the as-received Q235 steel, and four thermal-sprayed coatings steel have been investigated in simulated soil solutions in the present work. Some conclusions could be drawn as follows:

1) Pure Al coating, AlSi coating, NiAl coating and 316L stainless steel coating can significantly improve the corrosion resistance of Q235 steel in simulated soil solutions.

2) The results of electrochemical experiments and embedded sheets of substation show that AlSi coating has the best soil corrosion resistance, followed by NiAl coating and stainless steel coating, while pure aluminum coating is easy to bubbles and poor soil corrosion resistance.

3) The field bury tests prove that the thermal-sprayed AlSi coated Q235 steel had best corrosion resistance among the above three kinds of materials, suggesting that such kind of coating may be of great perspective to prolong the service life of grounding mesh.

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