Wear Mechanism of Current Collecting Materials under the Effect of Flowing Electric Current

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This paper proposes an electric contact model considering film resistance, such as an oxide layer, and describes a method for analyzing electric potential distribution and temperature distribution around a contact spot. As a result of the analysis, several laws governing the relationship between electric potential and temperature have been found, and a formula to calculate rising temperature was established using a factor calculated from contact resistance and film resistance. Finally, this paper proposes a map quantitatively showing transition conditions between wear modes.

Keywords: current collecting materials, potential distribution, temperature distribution, wear mode map

1. Introduction

Current collection installations, such as an OCS-Pantograph system, are used on electric railways, to enable effective supply of high power to vehicles from substations. In this type of system, parts such as the OCS contact wires and pantograph contact strips are collectively called “current collecting materials.” Since the life of these materials depends mainly on progress of wear, especially local wear which shortens the life of contact wires, it is essential to mitigate wear in order to reduce maintenance costs.

Conventionally, it has been thought that significant wear in current collecting materials is caused by arc discharges generated when contact loss occurs between the pantograph and the contact wire. Therefore, it was posited that one way to reduce contact loss and in turn mitigate wear, would be to improve the kinetic interaction between the pantograph and the overhead contact line. The wear mechanisms however, under the effect of flowing current are not yet clear, consequently, a fundamental measure to mitigate wear has not yet been proposed.

Test apparatus was therefore developed and wear tests were carried out to clarify these wear mechanisms. The results were reported in a paper [1] and demonstrated that there were multiple wear modes under the effect of flowing current which govern the wear of the current collecting materials. In the same paper, the author calculated the maximum temperature for the contact spot, based on the contact voltage measured during the wear tests, and found that the transition phenomena between wear modes were caused by the melting of contact members by Joule heating.

This paper proposes a new analysis method for electric potential distribution and temperature distribution around the contact spot. As a result of the analysis, a new formula was found for the relationship between electric potential and temperature. Finally, a wear mode map which quantitatively shows the transition conditions between wear modes was proposed.

2. Electric potential distribution and temperature distribution around contact spot

2.1 Analysis method

This chapter proposes a new analysis method for electric potential distribution and temperature distribution around the contact spot.

The analysis model is shown in Fig. 1. This model reproduces the contact between contact wire and contact strip both of which function as cylindrical electrodes of radius \( D \) [m] and length \( l \) [m]. The contact spot of radius \( a \) [m], is located at the center of the contact surface. The original feature of this model is that the oxide film and layer of wear particles which cannot be ignored in real railway conditions, are considered to form a film resistance of thicknesses \( d_1, d_2 \) [m] on the respective contact surfaces.

Since the distribution of electric potential and temperature in the circumferential direction of the cylindrical model are uniform, the model can be simplified into an axisymmetric shape resembling a piece of cake. Each electrode is divided into 30 x 30 grid meshes, and electric connections between the respective elements are set as shown in Fig. 2. The element at the center in Fig. 2 has an electric potential \( \varphi_0 \) [V] and a temperature \( \theta_0 \) [K], and the surrounding elements have electric potentials \( \varphi_1, \varphi_2, \varphi_3, \varphi_4 \) [V].

![Fig. 1 Analysis model](image-url)
and temperatures $\theta_1$, $\theta_2$, $\theta_3$, $\theta_4$ [K] respectively. The center element and the surrounding elements are connected with electric resistances $R_1$, $R_2$, $R_3$, $R_4$ [$\Omega$].

The electric potential of the center element is calculated by (1) using Kirchhoff’s law.

$$\varphi_0 = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4}\right)^{-1} \left(\frac{\varphi_1}{R_1} + \frac{\varphi_2}{R_2} + \frac{\varphi_3}{R_3} + \frac{\varphi_4}{R_4}\right)$$

(1)

The electric resistivities of the film resistances are supposed to be given by (2).

$$\rho_{\text{film}} = f_1 \rho_1, \quad \rho_{\text{film}} = f_2 \rho_2$$

(2)

where $\rho_{\text{film}}$ and $\rho_{\text{film}}$ are electric resistivities of the film resistances on the contact wire and on the contact strip [\Omega m]; $\rho_1$ and $\rho_2$ are electric resistivities of the contact wire and the contact strip [\Omega m]; $f_1$, $f_2$ are degenerate factors of the film resistances on the contact wire and on the contact strip. The condition $f_1 = f_2 = 1$ means that there is no film resistance on each contact surface.

Equation (3) is a stationary heat conduction equation between the adjacent elements when Joule heating is applied.

$$\frac{d\theta}{dx} - \frac{d\theta}{dx} = 0$$

(3)

where $\theta$ is a potential difference [V]; $\lambda$, a thermal conductivity [W/mK]. Equation (4) shows the temperature dependence of thermal conductivity and electric resistivity according to the Wiedemann-Franz law [2]. The one-dimensional difference (5) is obtained by substituting (4) into (3) and integrating (3).

$$\lambda = L\theta$$

(4)

$$\theta = \left[\frac{1}{2} \left(\theta_{x+1}^2 + \theta_{x-1}^2 + \frac{\rho_{x+1} + \rho_{x-1}}{\lambda} \frac{dx}{d\theta}\right)\right]^\frac{1}{2}$$

(5)

where $L$ is the Lorentz number ($= 2.4 \times 10^{-8}$ [K²/V²]). In order to analyze the temperature distribution in case of the two-dimensional electric connection shown in Fig. 2, (5) is converted to (6).

$$\theta = \left[\frac{1}{4} \left(\theta_{x+1}^2 + \theta_{x+1}^2 + \theta_{x-1}^2 + \frac{\Delta x}{2\theta} (\theta_{x+1} - \theta_{x-1}) + \frac{\rho_{x+1} + \rho_{x-1}}{\lambda} \frac{dx}{d\theta}\right)\right]^\frac{1}{2}$$

(6)

Since the time for the temperature to rise around the contact spot is short, a stationary analysis is applied instead of the non-stationary analysis used in a railway context, even though contact between the contact wire and contact strip is sliding.

For boundary conditions, the electric potential at the upper end of the contact wire was set to the contact voltage $V_c$, and while the electric potential at the lower end of the contact strip was set to 0 [V]. An iterative calculation was then carried out, so that (1) and (6) are established for all the elements, and the calculation terminated when the value change in each element reached a value less than $1 \times 10^{-6}$.

The analysis was carried out on a combination of hard-drawn copper contact wire and an iron-based sintered alloy contact strip, the material properties of which are shown in Table 1. Figure 3 shows the contact resistances calculated using the proposed analysis method and the following equation derived from the paper [3] with a contact voltage 0.4 [V].

$$R_t = \frac{\rho_{\text{film}} + \rho_{\text{film}}}{\pi D^2}$$

(7)

where $R_t$ is the theoretical contact resistance [m]; $R_t$, the electric resistance of electrode [Ω]; $R_e$, the electric resistance around the contact spot [Ω]; $R_c$, the electric resistance of the film resistance [Ω]. In Fig. 3, each difference between the analytical value and the theoretical value was less than 5.0 %. Figure 4 shows the maximum temperatures of electrodes which were calculated using the proposed analysis method and the following equation derived from the $\rho$-dependence theory [2] with the contact voltage 0.4 [V].

$$\theta_{\text{max}} = \left(\frac{\rho_{\text{film}}}{4L} + \frac{\rho_{\text{film}}}{4L} + T_0\right)^{\frac{1}{2}}$$

(8)

where $T_0$ is room temperature ($= 300$ [K]). In Fig. 4, each

| Table 1 Calculation conditions |
|--------------------------------|
| Material | Contact wire | Contact strip |
| Electric resistivity $\rho$ [$\mu\Omega m$] | 1.77 $\times 10^2$ | 0.40 |
| Heat conductivity $\lambda$ [W/mK] | 373.0 | 253.0 |
| Melting point $T_m$ [K] | 1334 | 1646 |
| Radius of electrode $D$ [m] | $300 \times 10^{-6}$ | $300 \times 10^{-6}$ |
| Length of electrode $l$ [m] | $300 \times 10^{-6}$ | $300 \times 10^{-6}$ |
| Radius of contact spot $a$ [m] | $100 \times 10^{-6}$ | $200 \times 10^{-6}$ |
| Degenerate factor $f$ | 1, 10, 100 |
| Thickness of film resistance $d$ [m] | $10 \times 10^{-6}$ | $10 \times 10^{-6}$ |
difference between the analytical value and the theoretical value was less than 3.0%.

This analysis method made it possible to execute the electric potential distribution and temperature distribution analysis the result of which was consistent with the \( \phi-\theta \) theory, taking into consideration the dissimilarity in metal contact between the contact wire, the contact strip and the film resistances.

### 2.2 Analysis result

First, an example of the electric potential distribution and temperature distribution on the cross section of the model without the film resistance is shown in Fig. 5. The voltage drop occurred mainly in the contact strip because the electric resistivity of the iron-based sintered alloy contact strip is much higher than that of the copper contact wire, and the temperature rose mainly in the contact strip. According to Fig. 5, the maximum temperature was reached in the contact strip, causing a difference in temperature between the contact wire and the contact strip. Figure 6 shows the relationship between electric potential and temperature in the electrodes. It was found that the relationship is forms a parabolic curve, and that the parabolic curve depends on the contact voltage. In this paper, the parabolic curve is referred to as the "electric potential-temperature parabolic curve."

Secondly, an example of the electric potential distribution and that of the temperature distribution on the cross section of the model with the film resistance only on the contact wire is shown in Fig. 7. Because of the film resistance, the voltage drop and the temperature around the contact spot are both higher than those shown in Fig. 5. Figure 8 shows the electric potential-temperature parabolic curve for the various values of the degenerated factor of the contact wire \( f_1 \). According to Fig. 8, the shape of the curve does not change with film resistance, while the position of the contact boundary between the contact wire and

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**Fig. 3** Comparison of the theoretical value and the analytical value of the contact resistance

| Contact Resistance (Ω) | Theoretical Value | Analytical Value |
|-------------------------|-------------------|------------------|
| \( f_1 = f_2 = 1 \)    |   100 μm         | 200 μm           |
| \( f_1 = f_2 = 100 \)  | 1000 μm          | 2000 μm          |

**Fig. 4** Comparison of the theoretical value and the analytical value of the maximum temperature

| Maximum Temperature [K] | Theoretical Value | Analytical Value |
|-------------------------|-------------------|------------------|
| \( f_1 = f_2 = 1 \)    |   100 μm         | 200 μm           |
| \( f_1 = f_2 = 100 \)  | 1000 μm          | 2000 μm          |

**Fig. 5** Analysis results of the model without film resistance (contact voltage: 0.4 [V])

**Fig. 6** Relationship between electric potential and temperature in the model without film resistance

**Fig. 7** Analysis results of the model with film resistance only on the contact wire (contact voltage: 0.4 [V])

**Fig. 8** Electric potential-temperature parabolic curve for various values of the degenerated factor of the contact wire \( f_1 \).
The ratio of the electric potential at the contact boundary \( \varphi \) to the contact voltage \( V' \) is defined as a constant \( \alpha \). Since the electric potential at the lower end of the contact strip is set to 0 [V], \( \varphi \) is equal to the voltage drop in the contact strip, so that \( \alpha \) could be given by the following equation with use of the constriction resistance and the film resistance of each electrode. In this paper, the constant \( \alpha \) is referred to as the “contact boundary factor.”

\[
\alpha = \frac{\phi}{V'} = \frac{\rho_2}{\rho_1 + \rho_2} \frac{f_1 d_f}{\pi a} + \frac{f_2 d_1}{\pi a} \quad (10)
\]

If there is no film resistance on each contact surface, the contact boundary factor \( \alpha_0 \) is calculated only with use of the values of electric resistivities of the contact wire and the contact strip.

\[
\alpha_0 = \frac{\rho_2}{\rho_1 + \rho_2} \quad (11)
\]

By using \( \alpha \), the temperature at the contact boundary is calculated by (12).

\[
\theta = \left[ \frac{V'}{L} \left( \alpha - \alpha_0 \right) + 300 \right]^{1/2} \quad (12)
\]

The maximum temperature of the contact wire and the contact strip is determined according to the value of \( \alpha \) as follows:

(i) \( \alpha > 0.5 \)
- Maximum temperature of the contact wire............. (12)
- Maximum temperature of the contact strip............ (8)

(ii) \( \alpha = 0.5 \)
- Maximum temperature of the contact wire............. (8)
- Maximum temperature of the contact strip............ (8)

(iii) \( \alpha < 0.5 \)
- Maximum temperature of the contact wire............. (8)
- Maximum temperature of the contact strip............ (11)

According to these equations, the maximum temperatures of each electrode is calculated with the contact voltage \( V' \) and the contact boundary factor \( \alpha \) as shown in Fig. 9. In these figures, the melting point of each material is shown with the dashed line. Finally, the melting conditions of each member are integrated into Fig. 10. Each wear mode transitions to the melting of each contact member [1], so
the wear modes were classified into four categories as follows:
(a) Mechanical wear mode: wear occurs in the region where both the electrodes do not melt. In this mode, the current does not affect the wear rate of the contact wire and the contact strip.
(b) Contact wire melting wear mode: wear occurs in the region where only the contact wire melts. In this mode, the maximum contact wire wear rate is reached, and the friction coefficient increases.
(c) Contact strip melting wear mode: wear occurs in the region where only the contact strip melts. In this mode, the maximum contact wire wear rate is reached, and the friction coefficient falls.
(d) Mixed melting wear mode: wear occurs in the region where both the electrodes melt. In this region, it is thought that the wear rate of the contact wire and the contact strip increase.

Figure 10 shows the wear mode transition conditions quantitatively, so the map is referred to as the wear mode map in this paper. The dominant parameters of the wear mode could be identified as the three following factors: contact voltage, melting point, and contact boundary factor $\alpha$.

4. Wear mechanism of the current collecting materials

In this chapter, the wear phenomena which could not be clarified in the previous report [1] is explained using the wear mode map, and the wear mechanism of the current collecting materials is discussed. Figure 11 shows the plots of the wear mode and the contour of the contact voltage obtained in wear tests [1].

(i) Occurrence mechanism of the mechanical wear mode
According to Fig. 10, the contact wire and the contact strip never melt when the contact voltage is less than 0.4 [V] because the maximum temperature of each electrode never exceeds the melting point of each material. Therefore, in Fig. 11, it is considered that mechanical wear mode applies to when the contact voltage is below 0.41 [V].

(ii) Occurrence mechanism of the contact wire melting wear mode
According to Fig. 10, the contact strip never melts when the contact voltage is equal to or above 0.4 [V] or less than 0.5 [V] because the maximum temperature of the contact strip never exceeds its melting point. The contact wire melts however when the contact boundary factor $\alpha$ falls into one of the following conditions:
(a) If there is no film resistance on either contact surface, the contact boundary factor $\alpha_0$ is calculated to be 0.96 by (11). In this case, the contact wire does not melt in Fig. 10, and the wear mode must be the mechanical wear mode.
(b) If there is a film resistance on the surface of the contact wire, $\alpha$ decreases and the temperature of the contact wire rises. Then if $\alpha$ falls below 0.8, the contact wire melts and the wear mode must be the contact wire melting wear mode.

Since the wear tests were carried out in the open air [1], an oxide film and wear particles on the contact surface could not be ignored. Therefore, in Fig. 11, it is considered that the contact wire melting wear mode occurred when the contact voltage was equal or over 0.4 [V] and less than 0.5 [V].
(iii) Occurrence mechanism of the contact strip melting wear mode

According to Fig. 10, the contact strip melts when the contact voltage exceeds 0.5 [V] in the range of $\alpha$ 0.5 or more. If the contact strip melts, a high resistance film such as an oxide film is generated on the surface of the contact strip, and $\alpha$ increases while the temperature of the contact wire falls. Therefore, in Fig. 11, it is considered that the contact strip melting wear mode occurred and the contact wire did not melt because the contact voltage exceeded 0.5 [V].

![Fig. 11](image)

**Fig. 11** Relationship between wear mode and contact voltage

5. Conclusions

This paper proposed an analysis model which takes into account film resistances on the contact wire and contact strip. Distributions of electric potential and temperature around the contact spot were analyzed to clarify the wear mechanism affecting current collecting materials under the effect of flowing current. The following results were obtained:

(i) The relationship between the electric potential and the temperature in the electrodes was shown as a parabolic curve referred to thereafter as the ‘electric potential-temperature parabolic curve’.

(ii) The shape of the curve depended only on the contact voltage, and not on the combination of materials or film resistance.

(iii) The maximum temperature of the curve occurred at the intermediate potential of the contact voltage following the $\varphi $-$ \theta $ theory.

(iv) The contact boundary between the contact wire and the contact strip in the curve changed with film resistance on the respective contact surfaces.

(v) A new proposal was made for a factor indicating the contact boundary between the contact wire and the contact strip, and the electric potential-temperature parabolic curve was formulated.

(vi) A proposal was made for a new wear mode map which quantitatively shows the transition conditions of wear modes under the effect of flowing current. The map allowed clarification of wear phenomena which had up until now remained unclear.

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