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Development of a Prediction Method for Temperature Rise in Connector Terminals under Steady Current Flow

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Abstract

This paper describes a prediction method for temperature rise in a pair of wired plug-and-receptacle electrical connector terminals under given constant current flow using three-dimensional structural, electrical, and thermal finite element methods (FEMs).

To predict temperature rise in terminals, we must estimate (1) Joule's heat generation under given current flow, (2) heat conduction in terminals and wires, and (3) heat dispersion, i.e., convection and radiation from the outer surface of terminals and wires into the atmosphere.

Electrical resistance, which causes Joule's heat generation, consists of three components; (1) conductive resistance in terminals and wire conductors, (2) contact resistance between terminals, and (3) connection resistance between terminal and wire conductor, for example, by crimping. The last two components have been difficult to calculate theoretically up to the present and this has been one difficulty in developing a temperature rise prediction method for terminals. However, for contact resistance between terminals, we have developed an estimation method incorporating a combination of terminal insertion simulation using structural FEM and theoretical calculation of contact resistance for a simple contact model.

Another difficulty in computing temperature rise in wired terminals using FEMs is that both terminals and wires must be modeled, i.e., divided into small finite elements. However, the complete modeling of terminals and wires becomes too time-consuming for computer calculation, so we have developed an alternative method combining thermal network model analysis for a single wire and electrical and thermal FEMs for terminals without wires.

Applying this method to the prediction of temperature rise under current flow up to 150A for type 9.5 terminals with 15mm^2 wires, the predicted terminal values have been satisfactory agreed to experimentally obtained values.

Keywords: electricity, finite element calculation, modeling, simulation, thermal management

1 Introduction

Temperature rise in electrical connector terminals is a phenomenon as a result of the difference between the Joule's heat generated under a given current flow and the heat dispersed from the outer surface of terminals and wires into the atmosphere.

If generated heat exceeds dispersed heat, the temperature rise in terminals will increase, and in the worst case, the connector assembly (terminals, wires, and insulators or "connector housing") will burn in service. Hence, the development of a terminal temperature rise prediction method is critical, especially for high current connector terminals used in HEV/EV motor driving systems.

In the field of temperature rise prediction for electrical connector terminals, particularly by using the finite element methods (FEMs), studies have been published by Zhu et al. [1] and Angadi et al. [2].

Zhu et al. reported FEM simulation for thermal shock tests of radio frequency connector terminals. They calculated variation in temperature and contact load for a pair of terminals under cyclic atmospheric temperature variation. In their study, they did not take into consideration Joule's heat generation under current flow.

Angadi et al. [2] calculated values using FEM for temperature distribution in electrical terminals taking into consideration the effect of contact resistance between terminals. In their study, they modeled wireless terminals assumed two-dimensional plane stress and perfectly elastic deformation for their model, and for simplicity, neglected the effect of heat convection and radiation from the outer surface of the terminals.

In this study, we attempt to predict the temperature rise in a wired pair of plug and receptacle terminals under given constant current flow using three-dimensional elasto-plastic structural, electrical and thermal FEMs, which take into consideration the effects of (1) contact resistance between terminals, (2) Joule's heat generation, (3) heat conduction in terminals and wires, and (4) heat convection and radiation from the outer surface of terminals and wires into the atmosphere.

Section 2 summarizes the theoretical calculation method for contact resistance in a previously developed simple contact model [3]-[5].

Combining the resulting theoretical calculation of contact resistance in a simple contact model and the computation of the contact areas between terminals using elasto-plastic structural FEM simulation for the terminal insertion, we can obtain the theoretical contact resistance between terminals.

Next, carrying out electrical and thermal FEMs for the mated terminal model with the heat transfer boundary condition at its bases for taking into the consideration the effect of heat exchange between terminal and wire, we can determine (1) the voltage drop, (2) the distributions of the current density, and (3) the temperature rise in terminals.

The temperature rise prediction values obtained by a series of FEMs are then compared with the values acquired in experimental temperature rise tests.

As a result, we can verify that the predicted values for temperature rise in the terminals agree satisfactorily to the experimentally obtained values.

2 Prediction method for contact resistance

2.1 Apparent and real contact areas

Holm [6] has proposed an electrical current flow mechanism for a pair of contact members which have real contact areas (called as "A-spots") in an apparent contact area, as shown schematically in Fig.1. This mechanism indicates that current flow is constricted near an apparent contact area and passes through A-spots formed between contacts.

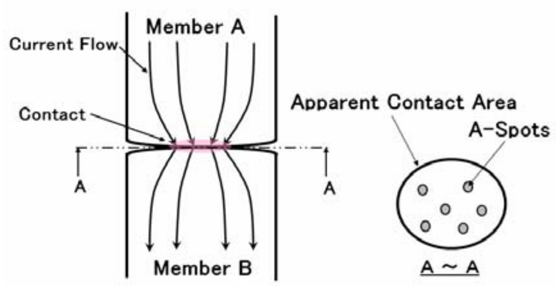

Figure 1: Schematic drawing of A-spots in an apparent contact area

Holm gives the contact resistance at a single A-spot as the sum of the constriction resistance R_c and the film resistance R_f as shown in Equation (1);

$$R = R_c + R_f = \frac{\rho}{2a} + \frac{\rho_f d}{\pi a^2} \tag{1}$$

where

ρ = resistivity of contact material

a = radius of A-spot

ρ_f = resistivity of film material

d = thickness of film

It has been reported that the constriction resistance is dominant over 10N of the contact load [7]. This value is similar to that for the high current terminals which we are studying.

Therefore, for convenience, we neglect the film resistance in this study.

In the case of a pair of contact members with A-spots in an apparent contact area, the constriction resistance has been formulated by both Holm [8] and Greenwood [9].

Equation (2) given by Holm shows the approximate constriction resistance with A-spots in an apparent contact area

$$R_c = \frac{\rho}{2A} + \frac{\rho}{2na} \qquad (2)$$

where
A = radius of apparent contact area
a = radius of A-spot
n = number of A-spots

However, it is difficult to measure the size and number of A-spots experimentally. This is a difficulty in calculating constriction resistance between contacts using Equation (2).

If the sum of real contact areas approaches the apparent contact area, the contact load becomes higher; the constriction resistance caused by the existence of A-spots, which is expressed by the second term of Equation (2), will be regarded as zero.

Hence, from the point of view of practical application, we assume that Equation (2) can be substituted for Equation (3) in this study.

$$R_c = \frac{\rho}{2A} \qquad (3)$$

2.2 Constriction resistance between contacts with plating layers

The constriction resistance for a pair of contacts with plating layers has been formulated theoretically by Tanii [10] as shown in Equation (4), obtained by multiplying the constriction resistance R_c in Equation (3) and the surface resistance coefficient Φ

$$R_c = \Phi \frac{\rho_1}{2A} \qquad (4)$$

where

$$\Phi = \frac{(1-K)}{(1+K)} \bullet \frac{1}{1 + \sum_{n=1}^{\infty} 2(-1)^n K^n F(2nt)}$$

$$K = \frac{\sigma_2 - \sigma_1}{\sigma_2 + \sigma_1}$$

$$F(x) = \int_0^{\infty} e^{-\lambda x} J_1(\lambda a) \frac{\sin(\lambda a)}{\lambda} d\lambda$$

ρ_1 is the resistivity of the contact (substrate) material, J_1 is the first-order Bessel function, σ_1 is the conductivity of the substrate material, σ_2 is the conductivity of the plating material, and t is the thickness of the plating.

2.3 Calculation of constriction resistance between terminals

As described in the previous section, the constriction resistance can be calculated for a given apparent contact area.

If the apparent contact area is related to the given contact load, the constriction resistance can be calculated for the given contact load, which is used as a common design parameter of terminals loaded using springs.

In this section, we explain the estimation method for the apparent contact area and the contact load between the plug and receptacle terminals using terminal insertion FEM simulation.

The obtained contact area can then be related to the constriction resistance as indicated in the previous section.

First, we estimate the relationship between the apparent contact area and the contact load for a pair of contact members (a rider and a flat plate) with plating layers using two-dimensional axis-symmetric elasto-plastic FEM analysis as shown in Fig. 2.

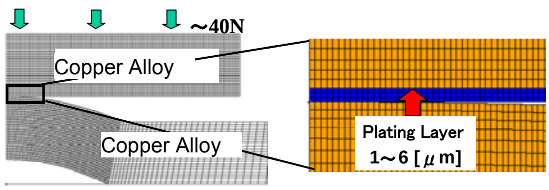

Figure 2: Two-dimensional axis-symmetric contact model with plating layer

Combining Equation (4) and the relationship between the apparent contact area and the contact load obtained by FEM shown in Fig.2, we can establish the relationship between the constriction resistance and the contact load. The calculation of the contact members with Sn plating (1 μm thickness) is indicated in Fig. 3, for example. The calculated contact resistance agrees with the value obtained experimentally in the region of the contact loads over 5N.

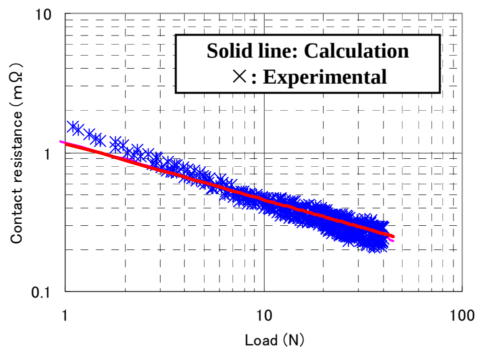

Figure 3: Comparison between calculated and experimental results for constriction resistance

Next, we apply this method to the estimation of the apparent contact areas between plug and receptacle terminals.

As our sample, we employ Sumitomo type 9.5 terminals made of heat-resistant Cu alloy with Sn plating. The flat blade-shaped plug terminal has a cross section of 9.5mm width × 1.2mm thickness, and the box-shaped receptacle terminal (1.2mm thickness) contains a stainless steel spring as shown in Fig. 4. The material properties are listed in Table 1.

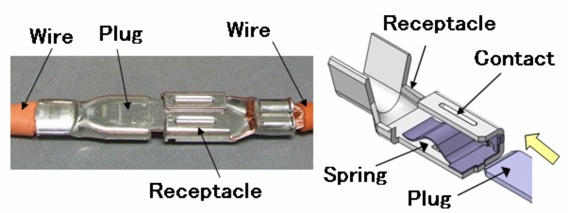

Figure 4: Sumitomo type 9.5 terminals

Table 1 Material properties of terminals

	Plug and Receptacle	Spring
Young's Modulus (GPa)	122	180
Poisson's Ratio	0.3	0.3
0.2% Proof Stress (MPa)	350	1400
Electrical Conductivity (S/m)	54	–
Thermal Conductivity (W/m·K)	355	16

The terminal insertion simulation is conducted using three-dimensional structural elasto-plastic FEM. A model cut in half longitudinally is adopted for its symmetry, as shown in Fig.5.

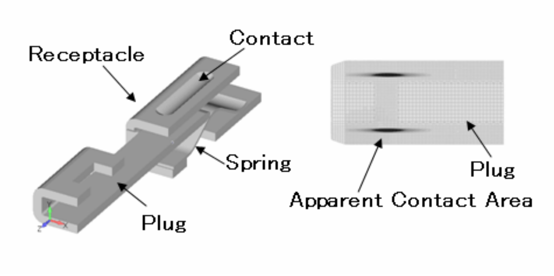

Figure 5: Terminal insertion simulation

After completing the insertion simulation, we can estimate the apparent contact area between the plug and receptacle terminals in the final mated position shown in Fig.5. In this case, the apparent contact area is estimated at 0.51mm^2 for each contact. This value is approximately equal to the value obtained by microscopic observation of the mated terminals.

Finally, the constriction resistance of 0.03mΩ between the terminals can be determined as described previously. In this estimation, we presume that electrical current does not flow through the spring, because the conductivity of stainless steel is very low.

3 Prediction of temperature rise in terminals

In this section, we explain the prediction method for temperature rise in terminals under given constant current flow using electrical and thermal FEMs and taking into consideration the calculated constriction resistance between terminals.

For the temperature rise prediction in terminals, we must estimate (1) Joule's heat generation, (2) heat conduction in terminals and wires, and (3) heat convection and radiation into the atmosphere from the outer surface of the terminals and wires.

In this study, we presume a mated model of the plug and receptacle terminals with wires as shown in Fig. 6.

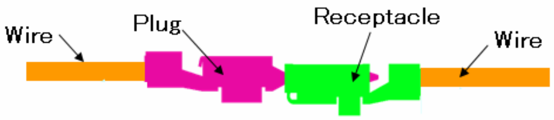

Figure 6: Analytic model of terminals and wires

To compute the temperature rise in the above model using FEM, both terminals and wires must be modeled, i.e., divided into small finite elements. However, the complete modeling of terminals and wires is too complex to solve, as it consumes too much computer time. Hence, we develop an alternative two-step method stated as follows (Fig. 7);

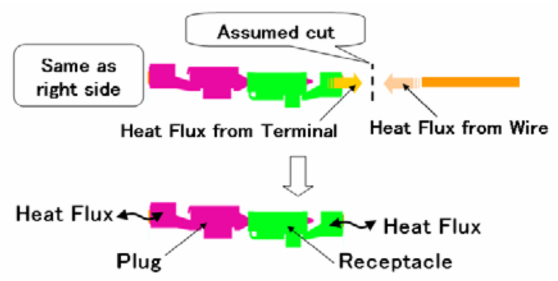

Figure 7: Alternative analysis method

First, we assume that the wire is cut at the base of the terminals and calculate the longitudinal temperature distribution of a single wire by thermal network model analysis to estimate the heat flux from the wire end.

Next, we solve the mated terminal model using FEM with the heat transfer boundary condition, which is derived from the above thermal network analysis, at its bases. Details are presented in the following sections.

3.1 Calculation of temperature distribution in a single wire using thermal network model analysis

The first step of terminal temperature rise prediction is calculating the longitudinal temperature distribution in a single wire for a given current flow using the thermal network model analysis shown in Fig. 8.

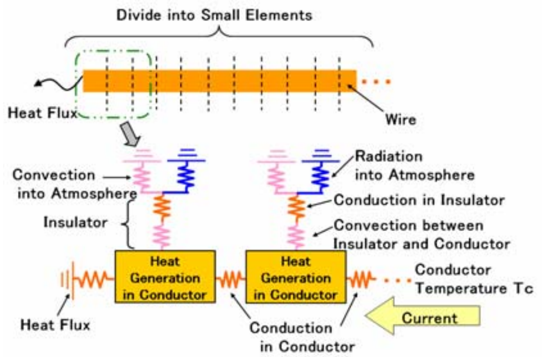

Figure 8: Thermal network model analysis of a single wire

The generated Joule's heat is transferred into the wire conductor and insulator and finally dispersed into the atmosphere by convection and radiation from the outer surface of the wire insulator.

Solving the thermal network model shown in Fig. 8 for the given current flow mathematically, we can obtain the longitudinal temperature distribution in the wire and the heat flux from the wire end, which provides the heat transfer boundary condition at both ends of the terminal model described in the next section.

3.2 Calculation of temperature distribution in terminals using FEM

The next step is constructing the mated terminal model shown in Fig. 9, where we again employ the type 9.5 terminals shown in Fig. 4.

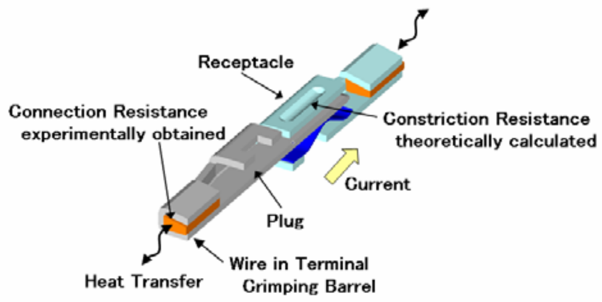

Figure 9: Mated terminal model

The heat transfer boundary conditions at its bases are determined as indicated in 3.1.

The calculated constriction resistance between terminals is also provided.

For the connection resistance between the terminal and the wire caused by crimping, we adopted a value obtained experimentally for the initial state, because it is difficult to calculate theoretically at the present time.

Solving the mated terminal model shown in Fig.9 using three-dimensional electrical and thermal FEMs, we can obtain results for (1) voltage drop, (2) current density distribution and (3) temperature distribution in the terminals.

As an example, we show the results of a voltage drop in Fig. 10, current distribution in Fig. 11 and temperature distribution in Fig. 12 for the type 9.5 terminals under 100A current flow. In this calculation, it is supposed that the 15mm^2 wires are connected at both ends. The parameters for heat dispersion from the outer surface of the terminals are determined experimentally from the results of the temperature rise test for the various-sized terminals.

In Fig. 12, the difference between the maximum and minimum temperatures is less than 2 degrees, which can be regarded as approximately constant.

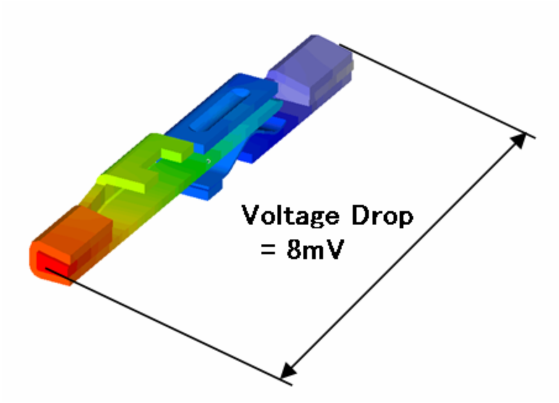

Figure 10: Voltage drop in terminals

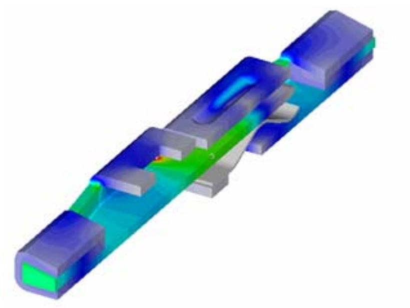

Figure 11: Current distribution in terminals

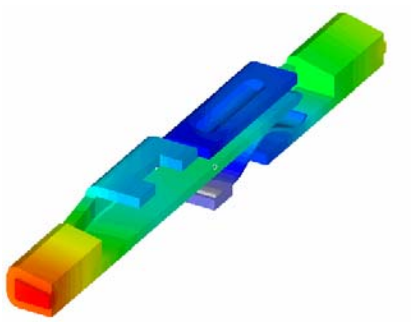

Figure 12: Temperature distribution in terminals

Fig. 13 compares predicted temperature rise values and experimentally obtained values in terminals. These results agree satisfactorily.

The developed analytic method has the advantage of shortening the calculation time compared to complete model analysis of terminals and wires, because the developed method does not include a finite element model for wires.

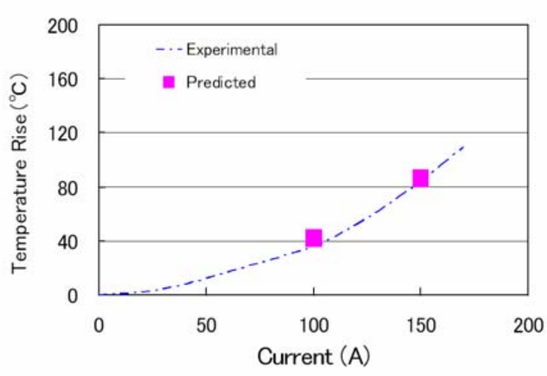

Figure 13: Comparison of predicted and experimental temperature rise

4 Conclusion

In this study, we have developed a prediction method for temperature rise in a wired pair of plug and receptacle terminals under constant current flow using three-dimensional structural, electrical and thermal FEMs.

Our results are summarized as follows;

1. The constriction resistance between plug and receptacle terminals has been estimated theoretically by combining three-dimensional elasto-plastic terminal insertion FEM simulation and theoretical calculation of constriction resistance for a simple contact model with plating layers.

2. Electrical current density distribution and voltage drop in terminals have been obtained for the mated terminal model using three-dimensional electrical FEM.

3. Temperature distribution in terminals has been obtained for the mated terminal model using three-dimensional thermal FEM.

4. Predicted values for temperature rise in terminals have been satisfactorily agreed to experimentally obtained values.

We conclude that the temperature rise prediction method described in this paper will be useful for terminal design.

In this study, we have not taken into consideration the effect of insulators ("connector housings"). Hence, our next target will be the determination of a prediction method for temperature rise for a complete connector assembly including insulators.

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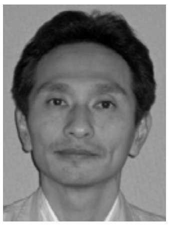

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