Simulation and experimental investigation of contact spot temperature for electrical contact components

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Abstract. The contact spot temperature of electrical contact components substantially affects the reliability and electrical life of any electrical connections within the electrical engineering. In this paper, finite element model of typical spring structure components is built by using COMSOL Multiphysics software. Furthermore, the transient process of contact temperature is simulated by taking account of film resistance on the contact surface. Moreover, a test rig is introduced that makes it possible to measure the electrical contact resistance and temperature within the electrical contact components simultaneously. Finally, correlation between contact resistance and contact spot temperature with different contact force and current levels are investigated explicitly.

Keywords: electrical contact; contact temperature; contact resistance; finite element simulation

1. Introduction
Current flowing through two separable electrical components is a typical electrical connection method within electrical apparatus. The features of contacts surface, rough and unclean, form the constriction resistance and film resistance of mated components. Contact resistance and contact temperature rise coexist for a long time and are influenced each other. Abnormal increase of contact resistance and contact temperature can induce electrical contact welding, short circuit, fire casualty and so on. The correlative factors include contact force, current, material physical properties and interface characteristics. Demand on low and stable contact temperature rise and contact resistance is increasing with the trend of system being adaptive in more complicated and extreme environments.

Relationship between temperature and contact voltage drop was firstly described by $\varphi$--$\theta$ relationship in Holm’s classical theory in condition of symmetric contact, and Timsit proved the validity of the theory in last century [1,2]. In recent years, analysis about contact resistance gradually enriched the electrical contact theory, which has considered factors including constriction radius [3], a-spot thickness [4] and heterogeneous materials [5] etc. The essential character that conductive spots are hidden in contacts outside surfaces poses challenges to identify the conductive surface and to measure the contact temperature. Swingler [6,7] obtained pictures of conductive area of bolted contacts using CT scan technology. Sawada [8] researched the current density distribution in contact surface by introducing semiconductor wafer experiment. Although there are already reports about
measuring instruments that can measure temperature and contact resistance, factors which correlative with temperature rise and contact resistance in electrical contact components are still insufficient.

Firstly, a new designed test rig for measuring the temperature rise and loop resistance of typical contact components simultaneously is introduced. The transient process of temperature rise and loop resistance is recorded with different contact forces and currents. In addition, the contact spot temperature rise is determined by comparing the finite element simulation results and the experimental results. The research method in this paper provide an alternative for evaluate the reliability of electrical contact components.

2. Numerical simulation of multi-physics field coupling

In order to accurately estimate temperature changes within the whole electrical contact components and contact spot temperature rise, this paper applies COMSOL Multiphysics 5.3a finite element software to establish a physical simulation model. 3D symmetric geometry and meshes are shown in Fig. 1.

![3D symmetric geometry and mesh](image)

(a) Illustration of electrical contact components  
(b) Simulation model

**Figure 1.** 3D symmetric geometry and mesh

The material properties used in the simulation are shown in Table 1. Firstly, structure mechanics module is called for determining the real contact radius. On this basis, an electric-thermal coupling analysis is performed sequentially. The initial ambient temperature is 28°C, which is room temperature of real experimental conditions. Set heat transfer coefficient of the interface of model. Thereby electric potential and the contact spot temperature \( T_m \) within the contact region will be obtained, as well as the entire potential distribution and the temperature distribution within the model. To analyze the effect of film resistance on the temperature during the increasing process, the interface element of contact resistance between the contact surfaces is added. The film resistance can be simulated by setting the surface resistivity. The complete multi-physics coupling simulation process is shown in Fig.2.

| Material                  | Beryllium bronze | AgSnO₂   |
|---------------------------|------------------|----------|
| Conductivity (S/m)        | 4.02×10⁻⁸        | 2.4×10⁻⁸ |
| Density (kg/m³)           | 8960             | 9800     |
| Elastic modulus (GPa)     | 26.8             | 79       |
| Poisson's ratio           | 0.35             | 0.37     |
| Heat capacity (J/(kg·K))  | 385              | 272      |
| Thermal conductivity (W/(m·K)) | 195            | 325      |
| Melting Point(K)          | 1356             | 1233     |

**Table 1.** Material properties used in simulation calculation
Start Build axisymmetric geometry model of sphere-plane contacts and set the material properties. Define the contact area and mechanical boundary conditions, and apply Structural Mechanics module to calculate the contact radius. Add interface contact impedance unit and set electric conductivity. Setting film resistance. (Optional) Define reference zero potential and current input area. Set heat boundary transfer conditions. Apply Joule Heat module to calculate potential field and temperature field of the contacts so as to obtain contact temperature and contact resistance. Simulation results agree with Experimental results? Yes No

End

Figure 2. Simulation flow chart

The steady mechanical stress, electrical potential and temperature distribution of electrical contact components with carrying current of 20A and movable contact bridge over travel of 1.8mm is plotted in Fig.3. As shown, the maximum von Mises stress reaches 53.34MPa, which is below the allowable stress of Beryllium bronze material. The maximum stress of contact region is only 3.06MPa, and the mechanical contact area of 0.27mm² could be exported from the results. Also, the distribution of electrical potential and current density flow route of cross section in Plane XY is illustrated in Fig.3(c). As expected, current density lines are obviously constricted into the mechanical contact zone, which results into the substantial potential drop. So, the maximum temperature of 317.69K also appears the center of mechanical contact zone. It should be noted that the contact spot temperature relates closely to the electrical contact situation. Once the temperature approaching the melting point of electrode material, the welding failure occurs certainly.

(a) Von Mises Stress (b) Zoom-in contact surface (c) Electrical current and potential

(d) Temperature distribution contour (e) Temperature situation of contact surface

Figure 3. Simulation results (convection coefficient is 14W/(K·m), and film resistivity is 0.1Ω·cm²)
Fig. 4 shows the variation in contact spot temperature rise as a function of time at 20A current loads. The steady temperature rise of contact spot is 61.75K. The changing rule of transient temperature rise follows negative exponent function, and the transient temperature rise of heating element can generally be written as

\[ \tau = \tau_w - (\tau_w - \tau_0) \exp(-t/T) \]  

where \( \tau_w \) is stable temperature rise, \( \tau_0 \) is initial temperature rise, \( T \) is thermal time constant.

![Temperature rise vs Time](image)

\[ \Delta T = 61.75 - 61.13e^{-t/68.93} \]

**Figure 4.** Variation in contact spot temperature rise as a function of time at 20A current loads

3. **Experimental method**

The new test rig is mainly composed of mechanical structure and measurement unit. The mechanical structure is mainly used for clamping real size electrical contact components and flexible mechanical loading in one dimensional direction. The maximum of loading cell is 5000cN and the sensitivity is 1.5 mV/V. Four-wire method is used to measure contact resistance with external controllable constant current source, and the current accuracy is 1%. Contact voltage and current are recorded by our designed signal amplification circuit. Temperature is measured by the miniature thermocouple electrical contacts. T type thermocouple is chosen, of which temperature measuring range is from -200°C to 200°C and the uncertainty is 0.2°C.

As shown in Fig. 1(a), the typical electrical contact component includes two static contact components and one movable contact bridge component. Rivets are silver tin oxide material, and the leaf springs are Beryllium bronze material. Specimens were degreased using acetone, methyl alcohol and distilled water in an ultrasonic cleaner in order, dried and carefully mounted in the test rig. The thermocouple is installed at the bottom of leaf spring. In order to improve the stability of the measurement, and reduce disturbance by environment factors like airflow, and temperature change and micro vibration, the mechanical structure part adopts is under protection of vibration isolation platform and transparent organic glass housing. Schematic diagram of test rig is shown in Fig. 5. Experimental condition is shown in Table 2.

| Table 2. Experimental condition |
|--------------------------------|
| Contact force | 0.01~1N       |
| Contact current | 5~50A        |
| Temperature    | 25±1°C       |
| Humidity       | 61±2%RH      |
The positions of temperature measurement

Figure 5. Mechanical structure of test rig. 1. Linear translation stage for moveable bridge component 2. Copper terminal 3. Force transducer 4. Base plate 5. Clamping structure for static contact component 6. Moveable bridge component 7. Support 8. Jackscrew 9. Static contact component.

The mechanical load force is flexible adjusted by using the displacement control of movable bridge component during experiment condition setting process. The displacement reference zero point is defined as the contact force is 0.01N, meanwhile the loop resistance is 319mΩ.

4. Experimental results and discussion

Fig.6 illustrates the relationships between contact force, loop resistance and movable contact bridge displacement. As shown in Fig.6(a), the contact load force increases almost linearly with the displacement. However, the loop resistance drops significantly when the displacement increases from 0 to 0.2mm. After that threshold value, the decent rate slows down. The simulation results agree well with the experimental results.

Fig.7(a) shows the measured transient temperature rise of static spring and movable spring. The steady temperature rise of movable spring end and static spring end are 19.9K and 14.8K individually. The corresponding thermal time constant is 265.8s and 469.2s respectively according to the
exponential function fitting results. It indicates that the heat dissipation of movable spring component becomes easier.

\[
\tau = 14.39 - 13.12e^{-\frac{t}{451.1}}
\]  
\[
\tau = 14.41 - 14.34e^{-\frac{t}{443.9}}
\]

Figure 7. Variations in temperature rise of electrical contact components as a function of time

In order to reoccur the experimental results in simulation model, and further investigate the influencing factors with the use of FEM model, we build the same geometry model and use the associated material properties. However, the suitable convection coefficient is needed to improve the simulation accuracy. After several simulation attempts, the convection coefficient of 8.38W/(m²·K) is determined as the optimal value. The simulation results of temperature rise with the use of such value is compared with the experimental results. And the fitting function of temperature rise with the use of experimental results is expressed as

\[
\tau = 14.39 - 13.12e^{-\frac{t}{451.1}}
\]

The fitting function of temperature rise with the use of simulation results is expressed as

\[
\tau = 14.41 - 14.34e^{-\frac{t}{443.9}}
\]

So, the simulation model and associated method is accurate enough to further analyze the influence relationship.

Variations in temperature rise as a function of time for current load of 20A and contact load force of 0.6N, 0.8N and 1N are plotted in Fig.8. As shown, the steady temperature rise is 17.75K, 16.08K and 14.46K individually when the contact force is 0.6N, 0.8N and 1N. And the thermal time constant remains about 450s. Therefore, the contact load force has negligible influence in the heat transfer process.

Variations in temperature rise as a function of time for contact load force of 0.8N and current load of 10A, 20A and 30A are plotted in Fig.9. As shown, the steady temperature rise is 7.04K, 20.72K and 49.92K individually when the current load is 10A, 20A and 30A.

Figure 8. Effect of contact load force on temperature rise of the static spring end (current load is 20A)
5. Conclusions
This investigation mainly aims to determine the effect of contact force and current on contact spot temperature and contact resistance of spring contact component accurately. A new test rig, which could measure contact resistance and contact temperature simultaneously between contact pairs with changeable static contact force is presented. The direct measuring temperature method, that is implanting the thermocouple within the real size rivet contacts, is realized successful. A multi-physics field coupling simulation method is proposed based on the finite element software COMSOL Multiphysics 5.3a. Considered both experimental results and simulation results, the highest temperature that is the contact spot temperature is determined accurately. The heat dissipation of movable spring component is easier than the static one. The steady temperature and the thermal time constant of the static contact pair is negatively correlated with the contact force. Meanwhile, the stable temperature and thermal time constant is positively correlated with the contact current. Increase of contact force and current will result in decrement of the contact resistance.

Acknowledgments
The authors express their gratitude for the kind support provided by The National Natural Science Foundation of China (Contract Number 51777039 and 51377029).

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