Model to Assess the Temperature of the Constriction Area of Joints Used in Electrical Power Engineering

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Abstract

A finite-element model that describes electrical and thermal flow processes on a constriction area or microcontact of an electrical joint used in electrical power engineering makes it possible to describe both the interaction of adjacent microcontacts and a microcontact's thermal instability more precisely than before.

Keywords: Microcontact, constriction area, thermal instability, finite-element model

1 Introduction

If two conductors are connected to each other by their surfaces, the current does not flow with a uniform distribution over the apparent contact area A_{app}. Depending on both the surface roughness and the contact hardness, the real contact area A_{re} is only a fraction of the total area A_{app} that participates in the current transfer. The part in which the current lines are constricted is called constriction area or microcontact (Fig. 1).

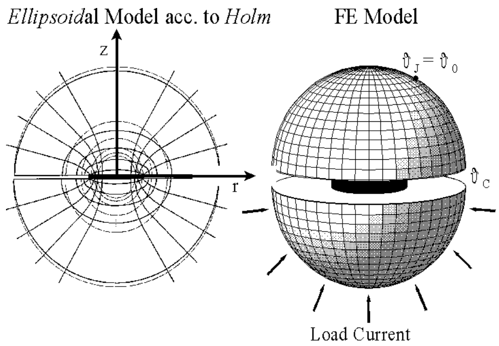


Fig. 1. Microcontact Models

In the microcontact investigated by *Holm* [1], the contact area is a circle with the radius a. Due to its ellipsoidal potential surfaces, this model is called *ellipsoid*al model. The contact resistance is

$$R_C = \frac{\rho}{2a} . \qquad (1)$$

The power losses produced in the microcontact is

$$P_C = I^2 R_C . \qquad (2)$$

The *ellipsoid*al model is based on the following assumptions:

- the microcontacts in an electrical joint have such a distance from each other on the apparent contact area A_{app} that their current fields do not influence each other;
- there is no continuous tarnishing film between the two halves of the microcontact;
- the microcontact's load current is so small that the power loss produced in it heats the joint only insignificantly.

These conditions are not fulfilled in electrical joints used in electrical power engineering. In the form of radiation and convection, the heat produced in the microcontacts is either transferred from the surface of the joint to the environment or is conducted along the conducting path into colder conductor sections. Therefore, the temperatures on the surfaces of the joints ϑ_J are higher than those of the environment ϑ_0.

The thermal resistance R_{th} of the *ellipsoid*al model can be calculated by the *Wiedemann-Franz-Lorenz*-Law [1] with

$$R_{th} = \frac{1}{16 \lambda a} . \qquad (3)$$

The temperature rise in the constriction area results from

$$\Delta\vartheta_{C,0} = P_C R_{th} . \qquad (4)$$

The aim of our further investigations is to calculate the temperature rise of the constriction areas $\Delta\vartheta_{C,0}$ by including both the specific electrical resistance ρ and the thermal conductivity 8, which are non-linear, temperature-dependent material data.

2 Thermal Independence of Adjacent Microcontacts

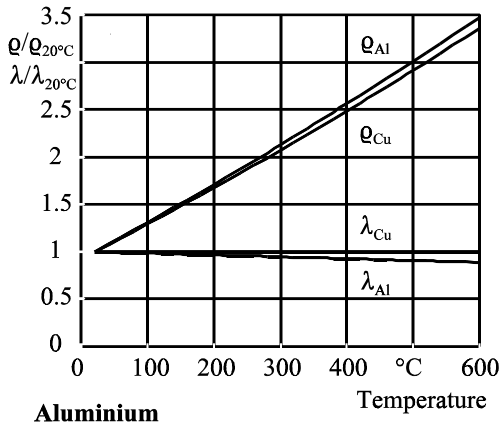
In case the temperature of the constriction area rises compared to the temperature on the surface of the electrical joint, both the electrical resistance, assumed to be

$$k(h) \; ' \; k_{20°C} \, (1 \; \% \; "_{Tk} \, (h \; \& \; 20°C) \; \% \; \$_{Tk} \, (h \; \& \; 20°C)^2) \quad (5)$$

and the thermal conductivity, assumed to be

$$8(h) \; ' \; 8_{20°C} \, (1 \; \% \; "_{T8} \, (h \; \& \; 20°C) \; \% \; \$_{T8} \, (h \; \& \; 20°C)^2) \quad (6)$$

have to be taken into account as a function of temperature. The linear and quadratic temperature coefficients of the specific electrical resistance $"_{Tk}$ and $\$_{Tk}$ respectively have been determined for the materials aluminium, copper and steel by resistance measuring up to 600 °C. The temperature coefficients of the thermal conductivity $"_{T8}$ and $\$_{T8}$ respectively have been taken from a relevant reference [3] (Fig. 2).



Aluminium

$\lambda_{20°C} = 221 W/Km$

$\lambda/\lambda_{20°C} = 1 - 2.0 \cdot 10^{-4} K^{-1} \Delta\vartheta + 1.0 \cdot 10^{-8} K^{-2} \Delta\vartheta^2$

$\varrho_{20°C} = 2.84 \cdot 10^{-8} \Omega m$

$\varrho/\varrho_{20°C} = 1 + 3.8 \cdot 10^{-3} K^{-1} \Delta\vartheta + 8.0 \cdot 10^{-8} K^{-2} \Delta\vartheta^2$

Copper

$\lambda_{20°C} = 393 W/Km$

$\lambda/\lambda_{20°C} = 1$

$\varrho_{20°C} = 1.80 \cdot 10^{-8} \Omega m$

$\varrho/\varrho_{20°C} = 1 + 3.6 \cdot 10^{-3} K^{-1} \Delta\vartheta + 8.0 \cdot 10^{-8} K^{-2} \Delta\vartheta^2$

Fig. 2. Material Data for Aluminium and Copper

With the help of the finite-element method (FEM) applied to the microcontact (Fig. 1), it has been investigated how far both the electric and the thermal potential field of the microcontact reach into the half space around the constriction area. The respective gradients of the electric and thermal field decrease with increasing distance from the constriction area. If the distance is 80 times the radius of the constriction area a, these approximation equations can be formulated: for the potential difference, $)n=U_C/2$ and for the temperature rise, $)h=0$ (Fig. 3). By means of these model parameters and the FEM, it can be determined whether or not the electric and thermal fields of adjacent microcontacts in electrical joints used in electrical power engineering influence each other. For this purpose, the related range k, which is a measure for the spread of the potential fields in the half space around the constriction area, is defined as follows:

$$k_{)h} \; ' \; \frac{r_{)h \, ' \, 0.05 \,)h_{C,0}}}{a} \qquad k_{)n} \; ' \; \frac{r_{)n \, ' \, 0.95 \,)n_{C,0}}}{a} \; . \quad (7)$$

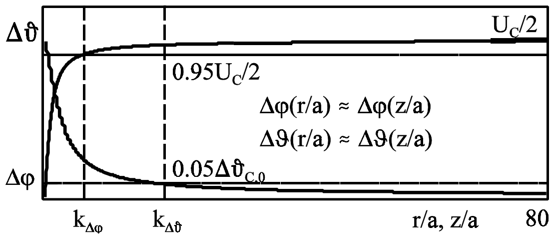


Fig. 3. Definition of the Related Range $k_{)n}$, $k_{)h}$

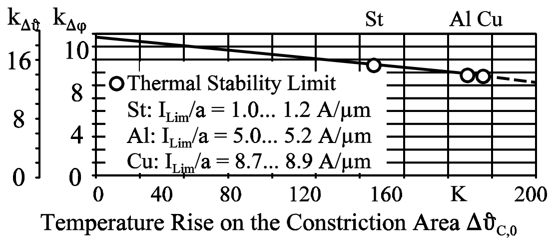


Fig. 4. Related Range of the Potential Fields

Both distances or ranges are related to the radius of the constriction area a. The distance at which 95% of the electrical potential difference $)n_{C,0}$ is reached is called related electrical range $k_{)n}$. The related thermal range $k_{)h}$, on the other hand, denotes the distance at which 5% of the temperature rise $)h_{C,0}$ is reached.

It has been found a relation of similarity which says that microcontacts with constriction areas different in size show the same temperature on their respective constriction areas if they are loaded with the same related current I/a.

$$)h \; ' \; I^2 R_C \, R_{th} \; ' \; I^2 \, \frac{k(h)}{2 \, a} \, \frac{1}{16 \; 8 \; a} \; - \; \frac{I^2}{a^2} \quad (8)$$

At the related ranges $k_{)h}$ and $k_{)n}$, almost spherical equipotential surfaces arise in horizontal (r) and vertical (z) direction to the constriction area (Fig. 1and Fig. 3). Therefore, the following relation can be formulated:

$$k_{\Delta\varphi;\Delta\vartheta}(z) \approx k_{\Delta\varphi;\Delta\vartheta}(r) \,. \qquad (9)$$

The penetration depth of the electrical field is

$$k_{\Delta\varphi} \approx 10 \qquad (10)$$

and the penetration depth of the thermal field equals

$$k_{\Delta\vartheta} \approx 20 \,. \qquad (11)$$

The related ranges for the investigated conductor materials aluminium, steel and copper decrease the more the temperature rises (Fig. 4). This has the following reason: whereas the specific electrical resistance grows with rising temperature (cf. equ. 5), the heat conductivity either remains constant or decreases (cf. equ. 6). The heat produced in the microcontact increases overproportionally to the square of the load current. The heat dissipation from the constriction area, however, deteriorates. As a consequence, the electric and thermal potential fields are constricted if the load current increases. This effect can be recognised by the decreasing ranges at higher temperature differences between the constriction area and the surface of an electrical joint (Fig. 4). Therefore, the electric and thermal potential fields of adjacent microcontacts do not influence each other if the distance between them is at least the double related range. At a constriction area radius of $a \approx 10\mu m$, the minimum distance between adjacent constriction areas amounts to 40a=0.4mm.

3 Thermal Instability of Microcontacts

The power losses due to current P_C that are produced in a microcontact in a thermally stable state are completely dissipated over the surface of the joint P_{th}:

$$P_C = P_{th} \,. \qquad (12)$$

If the power balance is disturbed to the effect that $P_C > P_{th}$, the microcontact is thermally unstable. This means that its temperature rises continuously. The thermal instability begins if

$$\frac{d}{d\vartheta} P_C = \frac{d}{d\vartheta} P_{th} \,. \qquad (13)$$

If the microcontact is only just in a thermally stable state, it reaches the limit temperature difference between the constriction area and the surface of the joint. In a thermally unstable state, the microcontact reaches the softening and melting temperature of the conductor material respectively only within a few milliseconds. The limit temperature difference depends on both the geometry of the constriction area and the thermal conditions on the surface of the joint. The current at which the microcontact becomes thermally unstable is called thermal limit current. With equ. (13), the thermal limit current I_{Lim} can be calculated approximately for the *ellipsoid*al model. If one relates this current to the radius of the constriction area a, one obtains a characteristic physical quantity by which the thermal instability of a microcontact can be calculated:

$$\frac{I_{Lim}}{a} \approx \sqrt{\frac{48\,\lambda}{\rho\,\alpha_T}} \,. \qquad (14)$$

The temperature coefficient α_T of electrical resistance for the conductor materials aluminium and copper amounts to $\alpha_T \approx 0.004K^{-1}$. If the specific electrical resistance ρ according to equ. (5) and the thermal conductivity λ according to equ. (6) are taken into account in the finite-element model (Fig. 1) as a function of temperature, the following approximation equation can be formulated:

$$\frac{I_{Lim}}{a} \approx \sqrt{\frac{(10.0...14.8)\,\lambda}{\rho\,\alpha_T}} \,. \qquad (15)$$

The temperature-rise limit in the constriction area of the microcontact can be calculated for Al and Cu according to equ. (8) and (15).

$$\Delta\vartheta_{C,0\ Lim} \approx 0.5\,\frac{1}{\alpha_T} \approx 125K \qquad (16)$$

Since microcontacts lead to a significant temperature rise on the surface of electrical joints used in electrical power engineering, the joints' thermal limit current has to be lower than the one calculated according to equ. (15). According to [4], the heat transfer resistance, which works from the surface O of the joint to the environment and considers both radiation α_r and convection α_c, can be calculated as follows:

$$R_{rc} = \frac{1}{(\alpha_r + \alpha_c)\,O} \,. \qquad (17)$$

Thus the related limit current of an electrical joint can be calculated:

$$\frac{I_{Lim}/a_{real}}{I_{Lim}/a_{ideal}} \approx \sqrt{\frac{1}{1 + \frac{R_{rc}}{R_{th}}}} < 1 \,. \qquad (18)$$

4 Investigations of Microcontacts in Joints of Electrical Power Engineering

In an electrical joint, many parallel microcontacts exist.

Neither their precise number nor the current density on the individual microcontacts have been able to be calculated up to now. Therefore, a finite-element model whose geometrical, electrical and thermal qualities result from the known parameters of the joint is built up for a microcontact. The FE model is a single microcontact that reproduces the electrical and thermal processes in all the microcontacts on average.

As an example, the model of a bolted joint that connects two overhead line conductors ACSR 240/40 mm² with each other has been chosen (Fig. 5). The joint consists of two halves. These are connected to each other by means of three bolts. In order to facilitate a better contact between the two conductors, 96 grooves are cut into the contact areas of the joint's halves. The conductors consist of a total of 26 twisted aluminium wires that enclose a seven-wire steel core (Fig. 5). Out of the 26 aluminium wires, 16 are located on the rope's outer layer. The current carrying capacity of the conductor amounts to I_r=645A. The following assumptions are made for the set up of the FE model:

C all the microcontacts of the bolted joint have the same geometry, are distributed evenly in the joint and are loaded with the same current;
C the thermal and electric fields of adjacent microcontacts do not influence each other (cf. sec. 2);
C the load current flows, distributed in parallel, out of each of the 16 outer wires of conductor line 1 over each of the 96 grooves of the joint's halves into the upper and lower half respectively and from there into conductor 2; this leads to a maximum number of 2·96·16=3072 microcontacts; if only one groove gets into electrical contact with one wire of both outer rope layers, a minimum number of 32 microcontacts is the consequence;
C the heat loss due to current produced in the halves of the joint can be neglected because of the low material resistances; the heat loss due to current in the microcontacts and the outer layers of the conductors in the bolted joint is taken into account;
C a direct-axis current flowing along the outer layer of the respective conductors in the joint and a cross current flowing through the microcontacts along the joint are assumed [5];
C the microcontact is connected with the environment by a heat transfer coefficient of radiation and convection on the surface of $"_{rc}$=16W/m² K;
C depending on the temperature difference between joint and conductor $) h_{J,L}$, a power exchange takes place.

It has been chosen a finite-element model that consists of two cylinders connected to each other by a microcontact with the variable radius a and a tarnishing film with the variable thickness s_t. Whereas the upper cylinder of the contact model represents the volume of the bolted joint related to the microcontact, the lower one models the volume of the conductor section in the joint related to the microcontact. The advantage of the rotationally symmetric geometry of the FE model lies in fact that the three-dimensional field problem can be reduced to a two-dimensional one by a coordinate transformation (Fig. 5).

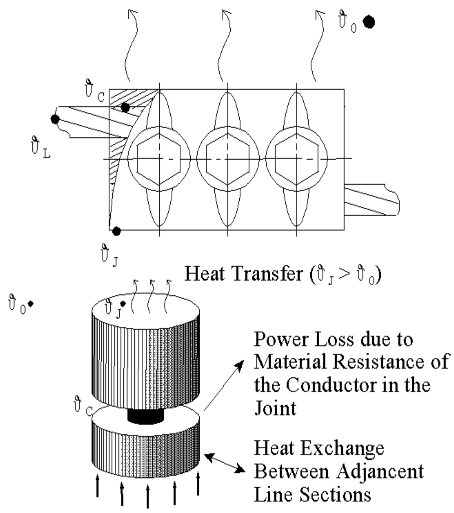


Fig. 5. Model of a Microcontakt in a Bolted Joint

If the microcontacts have a tarnishing film with the film resistance $F=k_t\, s_t$, they all show, acc. to equ. (8),

$$) h_{C,J} \,'\, I^2\left(\frac{k(h)}{2a}\,\frac{1}{16\,8\,a} \,\%\, \frac{F(h)}{B a^2}\,\frac{1}{8\,8\,a}\right) \,-\, \frac{I^2}{a^2}\left(k(h) \,\%\, \frac{4}{B}\,\frac{F(h)}{a}\right) \quad (19)$$

the same temperature difference with regard to their respective surfaces provided that the proportionalities I - a and F - a exist. Considering these proportionalities, the temperature rises on the constriction areas will not differ for the cases of 32 and 3072 microcontacts. A change of the thickness of tarnishing film s_t and the radius of constriction area a in the technically relevant ranges of

$$0 < s_t < 100 \text{ D} \quad und \quad 0 < a < 1000 \ \mu m \quad (20)$$

results in a parameter field for which the temperature difference between constriction area and surface of the joint $) h_{C,J}$ for 32 and 3072 microcontacts is calculated (Fig. 6). It has turned out that a thermally stable state does not exist with certain parameter combinations (a, s_t). As expected, both the temperature difference between constriction area and surface of the joint $\Delta\vartheta_{C,J}$ and the joint's temperature rise inverse proportionally to the radius of the constriction area a and proportionally to the tarnishing film s_t.

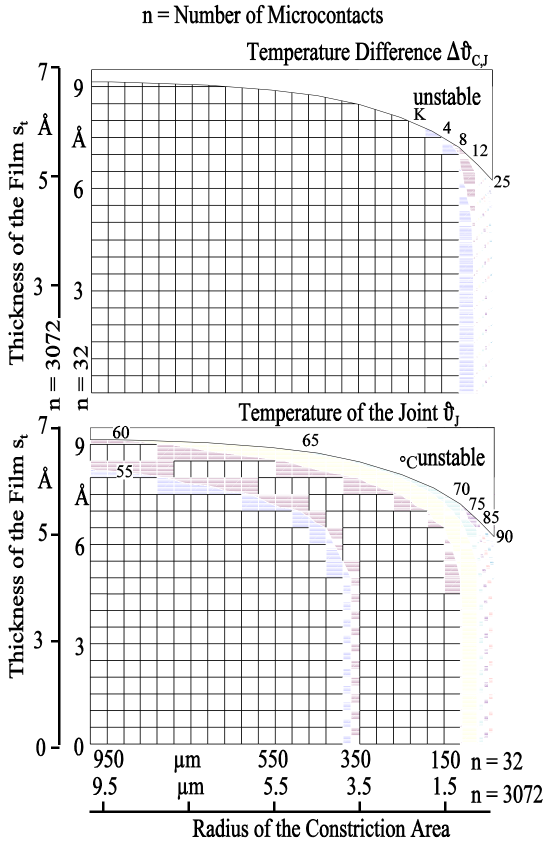


Fig. 6. Temperatures of the Bolted Joint

If the limit temperature difference $\Delta\vartheta_{C,J}$ is reached, the heat produced by the microcontact is permanently higher than the heat dissipated from it. The microcontact melts on the constriction area.

The temperature difference between constriction area and surface of the joint can be calculated, according to [1], with the following equation (Fig. 7):

$$\Delta\vartheta_{C,J} = \sqrt{T_J^2 + \frac{R_C^2\, I^2}{4\, L}} - T_J\ . \qquad (21)$$

The lower values of limit temperature differences for microcontacts in joints of electrical power engineering calculated $\Delta\vartheta_{C,J\,Lim}$ according to equ. (18) have been confirmed experimentally.

For the investigated bolted joint and at a related limit current of $I_{Lim}/a \approx 1\,A/\mu m$, they amount to

$$\Delta\vartheta_{C,J\,Lim} \approx 25K\ . \qquad (22)$$

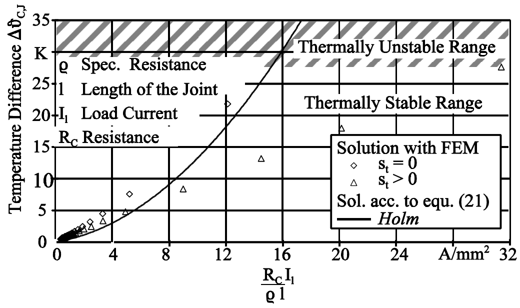


Fig. 7. Temperature Difference in a Bolted Joint

5 Conclusion

The investigations have shown that the temperature difference between constriction area and surface of the electrical joint can be calculated with the model suggested by *Holm* if no tarnishing films occur. It has to be taken into account that a thermally stable state does not exist anymore if the limit temperature difference and the related limit current for the microcontact respectively are reached. As far as joints used in electrical power engineering are concerned, this limit depends considerably on both the geometry of the joint and the geometry of the microcontact.

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