Mathematical model of the arc erosion in bimetallic electrical contacts

S.N. Kharin
Kazakh-British Technical University
KBTU
Almaty, Kazakhstan
staskharin@yahoo.com

H. Nouri
University of the West of England
Bristol, UK

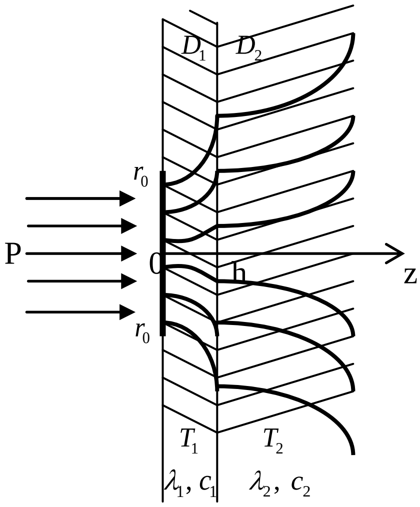
B. Miedzinsky
Institute of Innovative Technologies EMAG,
Katowice, Poland

***Abstract*-The mathematical model describing the non-stationary temperature field in a bimetallic contact consisting of a basic material and a covering is presented. It is based on the axially symmetric heat equation with the boundary conditions including an arc heat flux entering the covering surface and the ideal heat contact on the interface between covering and the basic material. The arc heat flux consists of the several components relating to the heating due to the electron and ion bombardment, arc radiation, inverse electrons, and cooling due to the electron emission, melting and evaporation. The dynamics of all these components is calculated for the brass contacts with the $AgCdO$ covering. It is found that the transition from the metallic arc phase to the gaseous arc phase occurs due to dynamical redistribution of the arc heat components. The resulting temperature fields in the basic contact and the covering enable us to choose the parameters for the optimal thickness of covering.**

Keywords - electrical contacts; surface coating; arc erosion; mathematical model

I INTRODUCTION

Bimetallic electrodes and electrical contacts consisting of a basic material and thin covering find an application for plasma generators, electrical apparatus, micro-electronics and many other fields. The problem of the optimal choice of the parameters of a covering is discussed in many papers. One of the first important parameters is the thickness of a covering which rational minimization enables one to provide saving of a noble and deficit material. The problem of the limiting thickness of a covering from noble metals (gold, platinum, palladium) providing reliable protection against aggressive surroundings and fretting-corrosion has been discussed in the papers [1]-[2]. The influence of a current range on this limiting thickness is considered in the paper [3]. It was found [5]-[6] that it is important for the silver-based coverings (Ag, AgCdO, AgCu) not only the condition of the contact surface but also the quality of the interface surface between the covering and the basic material (copper, brass, nickel etc.). However the covering problem is considered in all mentioned above papers only with relation to corrosion and the surface fretting, while the not less important factor of the arc erosion of a covering at the current commutation remains to be not considered practically except for some publications for solely specific cases [7]-[8]. The experimental investigations of dynamical phenomena in this direction which are of very short duration involve difficulties. Therefore the mathematical modeling of such phenomena seems to be very important.



II. MATHEMATICAL MODEL

Fig. 1 Temperature field in a bimetallic contact

Fig. 1 depicts the temperature field (axial section) in a bimetallic contact with coating D_1 of the thickness h and the basic material D_2. The arc heat flux entering the contact is P and the arc contact spot is r_0. This field is described by the heat equation

$$c_i\gamma_i \frac{\partial T_i}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda_i \frac{\partial T_i}{\partial r}) + \frac{\partial}{\partial z}(\lambda_i \frac{\partial T_i}{\partial z}) \quad (1)$$

with the boundary conditions

$$z = 0 \qquad -\lambda_1 \frac{\partial T_1}{\partial z} = P(r,t) \qquad (2)$$

$$z = h \qquad T_1 = T_2 \qquad \lambda_1 \frac{\partial T_1}{\partial z} = \lambda_2 \frac{\partial T_2}{\partial z} \qquad (3)$$

The main problem of this model is the determination of the arc heat flux entering the anode $P(r,t) = P_a(r,t)$ and the cathode $P(r,t) = P_c(r,t)$. This flux can be found from the equation of the arc energy balance

$$c_A \frac{\partial T_A}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(\lambda_A r \frac{\partial T_A}{\partial r}) + P_A(r,t) - P_a(r,t) - P_c(r,t)$$
$$0 \le r < r_A(t) \qquad (4)$$

where

$$P_A(r,t) = P_J(r,t) + P_L(r,t)$$

is the total heat flux generated by the arc, $P_L = -LI\frac{dI}{dt}$ and $P_J = IU = \frac{I(t)^2}{\sigma_A(T_A)\pi^2 r_A(t)}$ are its inductive power and Joule components entering anode and cathode. These components should be calculated taking into account the electron and ion bombardment of electrodes, their heating due to arc radiation and cooling due to melting and evaporation, and also cathode heating due to inverse electrons from the arc column and it's cooling due to electron emission [9]. All these heat flux components can be represented in the axial symmetric model in the form of normal distribution:

$$P_i(r,t) = \frac{2}{\sqrt{\pi}} P_i(t) \exp[-\frac{r^2}{r_i(t)^2}] \ ,$$
$$i = J, L, a, c \qquad (6)$$

with unknown functions $P_i(t),\ r_i(t)$ which should be found in the course of solution.
The corresponding components of the power can be defined by integration of the expressions (6) along the contact plane:

$$Q_i(t) = 2\pi \int_0^\infty P_i(r,t) r dr = 2\sqrt{\pi} r_i(t)^2 P_i(t) \qquad (7)$$

III. RESULTS OF SOLUTION

The calculation is carried out for the brass electrical contacts with $AgCdO$ coating for the following parameters: thickness of coating $h = 1\ mm$, opening velocity $V = 0.2\ m/s$, current $I = 10A$, voltage $U = 40\ V$ and inductance $L = 10\ H$ as shown in Fig. 2.

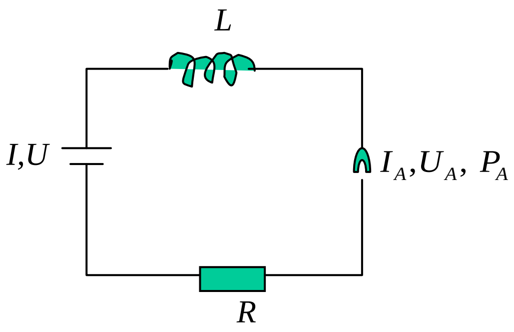


Fig. 2 Electrical circuit

The dynamics of the current, the voltage and the components of the arc power are given in Figs. 3 to 5.

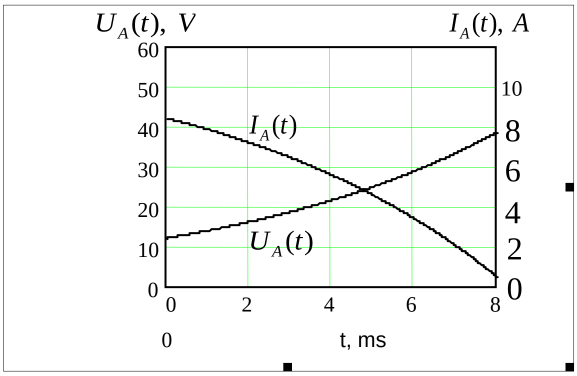


Fig. 3 The arc current and voltage

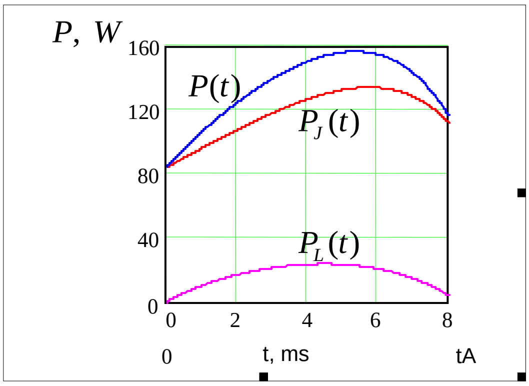


Fig.4 Dynamics of the arc power components

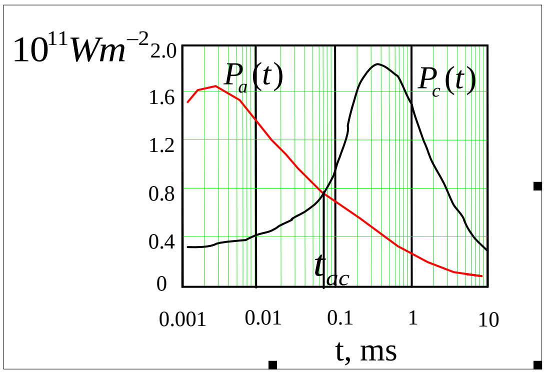


Fig. 5 Heat fluxes into anode and cathode

The following analytical expressions for the arc voltage and current are obtained:

$$U_A(t)=U_m\exp(kt/t_A),\quad I_A(t)=I\left[1-\frac{U_m}{U}\exp\left(-\frac{t}{\tau}\right)\right]$$

$$+\frac{U_m}{L(1/\tau+k/t_A)}\left[\exp\left(-\frac{t}{\tau}\right)-\exp\left(\frac{kt}{t_{AQ}}\right)\right]$$

where the constant k can be found from the solution of the transcendent equation

$$A+Bk+e^k=0,\quad A=\frac{U}{IU_m}\left\{I_m-I\left[1-\frac{U_m}{U}\exp\left(-\frac{t_A}{\tau}\right)\right]\right\},$$

$$B=\frac{L}{U_m t_A}\left\{I_m-I\left[1-\frac{U_m}{U}\exp\left(-\frac{t_A}{\tau}\right)\right]\right\}$$

Here t_A is the arc duration, I_m, U_m are minimum threshold values of the arc current and voltage (for $AgCdO$ $I_m=0.4\ A$, $U_m=12\ V$). Also, it was found also that the arc duration $t_A=8\ ms$.

From inspection of Fig. 5 one can conclude that the inductive component of the power is relatively small in comparison with the Joule component for the considered case. However the calculation shows that already at $L=50\ mH$ the situation is inversed and essentially the arc duration increases.

The dynamics of the heat fluxes into anode and cathode shown in Fig. 5 depicts two arc phases, the anodic arc phase with the material transfer from anode to cathode (the metallic mode of the ion current) and the cathodic arc phase with the inverse material transfer (mainly the gaseous mode of the ion current). The point of intersection $t=t_{ac}$ corresponds to the transition from anodic to cathodic arc phase. The temperature of the gas ionization reaches a little bit later, thus the cathodic phase begins at the metallic mode although its duration is small. A certain time after this moment is required for the inverse material redeposition from the cathode to the anode.

The determination of the time $t=t_{cr}$ when the purely cathode losses begin is very important for the minimization of the arc erosion, which can be attained at the arc switching off at this time.

The results of calculation of the dynamics of the cathode loss and gain given in Fig. 6 are in a good agreement with the experimental data [10]-[11]. The results of the calculation of the temperature fields into cathode are shown in Figs. 7 to 9 which reveals its dependence on the time and the thickness layer.

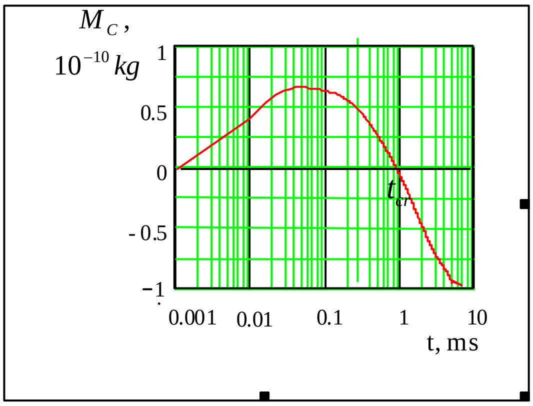


Fig. 6 Dynamics of the cathode erosion

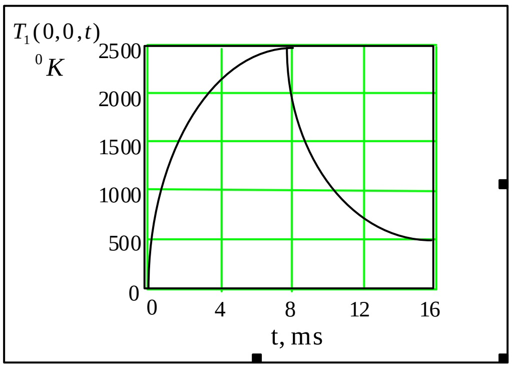


Fig. 7 The temperature at the centre of the arc spot on the cathode

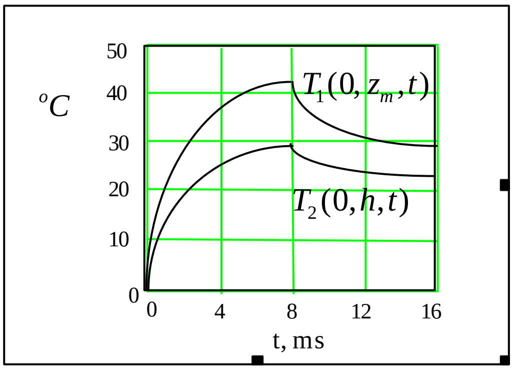


Fig. 8 The temperature inside the covering

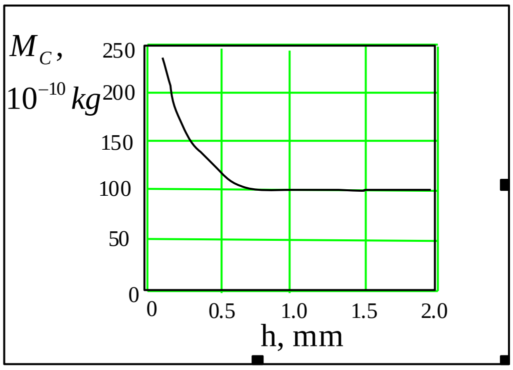


Fig. 9 Dependence of erosion on the thickness of the covering and on its interface with the electrode

Fig. 7 shows that the temperature at the centre of the arc spot on the cathode decreases very quickly due to a good heat transfer inside the brass electrode. The calculation shows that for electrode with a worse heat conductivity (nickel, iron) the decrease of temperature is essentially slow, that leads to the increase of the arc erosion. The thickness layer for such materials should be about 30% greater in order to provide the same level of erosion like for the brass contacts. The rate of change of the temperature on the interface between the base material and layer $T_2(0,h,t)$ and inside layer $T_1(0,z_m,t)$ (z_m is the point where temperature is measured by the thermocouple) is shown in Fig. 8 which is essentially low. These calculated data are in a good agreement with the results of measurements [10]-[11].

The results of calculation presented in Fig. 9 show that the dependence of erosion on the thickness layer is considerable in this case for the values of thickness which are not greater than 0.6 mm only. This threshold value can be considered as the main criterion for the choice of the lower limit of the thickness covering. Another criterion is the temperature limit on the interface between the layer and the base material. It should not be greater than the threshold temperature of phase transformation (softening and stress of the material). The corresponding upper limit is determined by the corrosion process on the outside surface during performance of the contact system.

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