ISSN 1068-3755, Surface Engineering and Applied Electrochemistry, 2018, Vol. 54, No. 1, pp. 96–102. © Allerton Press, Inc., 2018.
Original Russian Text © A.M. Chalyi, V.A. Dmitriev, M.A. Pavleino, O.M. Pavleino, M.S. Safonov, 2016, published in Elektronnaya Obrabotka Materialov, 2016, No. 6, pp. 12–18.

On Peculiarities of Welding and Destruction of the Surface of High-Current Layered Contacts by Pulsed Currents

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Received October 26, 2015

Abstract—Numerical modeling of the impact of short-duration pulsed currents on closed high-current copper-coated aluminum contacts is carried out. The modes of the current effects are studied which induce a significant contact area heating and cause melting and welding of the contacts. The influence of the copper coating thickness on the dynamics of the heating of the contacts is determined. In the course of the experimental study of the action of the shock short-circuit currents on the layered contacts, a comparative analysis was carried out of the resistance of the copper coating to such actions. The latter was manufactured using the sputtering and plating techniques. The heating levels of the contact surface, which cause its destruction during the breakup of the occurring thermal bonds, are determined. The destruction of the sputtered coating is observed to occur as soon as the stage of the diffusion welding begins, whereas the plated layers are not significantly damaged at the same current levels.

Keywords: electric contacts, pulsed heating, contact spot, constriction resistance, layered structure

DOI: 10.3103/S1068375518010027

INTRODUCTION

Recently, there has been a tendency toward replacement of copper elements of high-current conducting systems with the less expensive aluminum analogs [1]. However, the direct replacement is not always possible because of different properties of copper and aluminum, such as the specific resistance and temperature of melting, or because of different technological capabilities of their treatment, e.g., electroplating, and for a number of other reasons. Some of such problems can be solved using components with a layered structure. This work studies high-current aluminum contacts whose surface is plated with a copper layer. The right choice of the coating thickness and of the method of its plating ensures that the resistance of these coatings to shock short-circuit currents is the same as that of pure copper.

There are a few methods of copper plating on aluminum. The most commonly used are sputtering and plating [2, 3]. The copper layers coated on an aluminum substrate using the aforementioned methods differ from each other in the degree of surface roughness and in the strength of adhesion to the substrate. This can result in their different resistance to the welding breakups, which occur during the passage of a shock short-circuit current through the closed layered contacts. This is the main object of our study.

NUMERICAL MODELING

Let us perform the numerical calculation of heating of the copper-coated aluminum contacts by the pulsed current of sinusoidal form with duration of $\tau = 10$ ms. Current effects close in form were applied in the experimental studies. As the contacts, we choose coaxial cylindrical aluminum electrodes with a copper coating with thickness d, connected by a single contact spot of a circular shape with radius a located on the symmetry axis. Figure 1 shows a section view of a calculation model with the indication of the current lines and the lines of equal potential.

Let us analyze the effect of the coating thickness on the heating of the contact area. The process of passing of the current through the contacts without taking into account the thermoelectric effects can be described by the following system of equations:

$$\nabla \vec{j} = 0, \tag{1}$$

$$\gamma c_p \frac{\partial T}{\partial t} - \nabla(\kappa \nabla T) = \rho j^2, \qquad (2)$$

where T is the temperature, j is the electric current density, ρ is the specific resistance, κ is the thermal conductivity, γ is the density, and c_p is the heating capacity. To date, there is no general opinion as to whether or not thermoelectric currents must be considered during the heating of the high-current electric contacts [4, 5]. However, when the contact surfaces are made of copper, they can be neglected in the presence of the conduction currents [6].

Works [7–9] show that, in the case of copper electrodes, the dependence of the spot radius on time is well described by a bilinear curve. As long as the temperature of the contact is less than temperature of the material softening, the radius of the contact spot differs insignificantly from the initial value ($a = 0.5$ mm in further calculations). Then it starts to increase, with the rate of the radius increase remaining almost unchanged up to the beginning of softening. Let us accept such an approximation during the calculations in the case of layered contacts.

Figure 2 shows the dependences on time of the maximum temperature of the contact spot of aluminum electrodes for different thickness values of the copper coating (solid curves). The current value was selected so as in the process of heating the temperature of melting copper was reached. Those graphs show the heating curves for pure copper contacts at the same value of the passing current (dashed curves).

With the selected current pulse duration, the difference in the heating of the contact spots of the layered and pure copper electrodes (because of different thermophysical properties of copper and aluminum) becomes noticeable at small thicknesses of the copper layer compared to the size of the contact spot. Thus, with the layer thickness equal to half the radius of the contact spot, the temperature reached exceeds by over 500°C the temperature of the contact spot of the copper electrodes. These coatings will significantly decrease the resistance of the contacts to similar current impacts. However, at a thickness that is equal to the spot diameter, the curves of heating almost coincide.

Figure 3 shows the dependence of the amplitude of current that induces melting of the contact spots on the coating thickness. At $d \geq a$, the current which melts copper and layered electrodes differs by less than 5%.

The obtained data on the influence of thickness of the copper layer on heating of the layered electrodes were used for manufacturing the layered contacts in the experimental studies. The coating thickness was selected so that the heating temperatures for the layered and copper contacts were close.

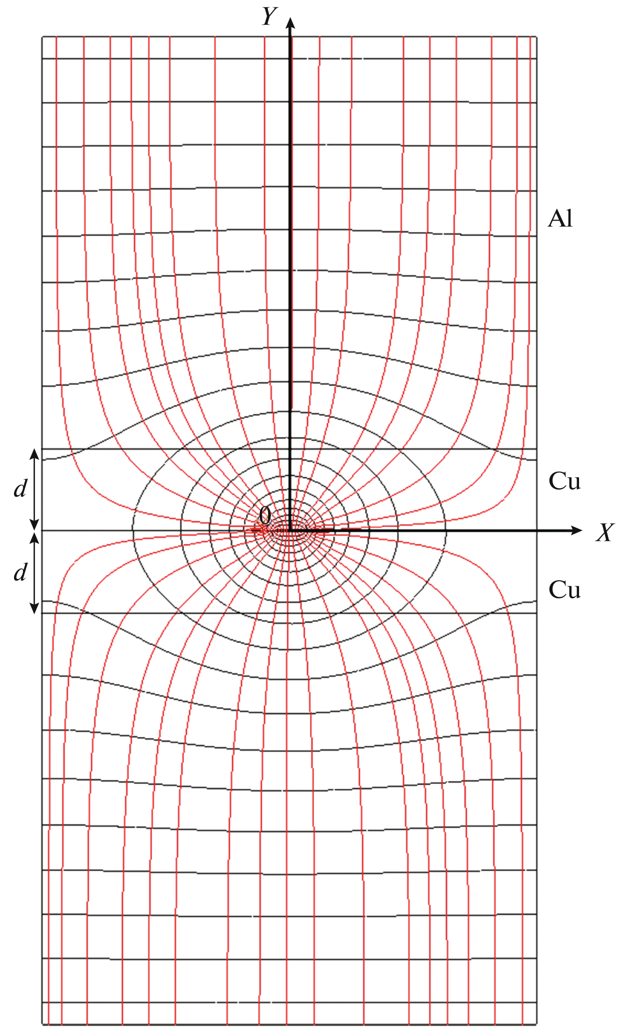

Fig. 1. Model of layered contacts. Distribution of lines of current and lines of equal potential.

EXPERIMENTAL

The aim of the experimental study of the action of shock currents on copper-coated aluminum contacts is to examine the initial stage of occurrence of the welding of such contacts and to determine the maximum permissible levels of the shock current for the coatings of the two most popular types, namely, sputtered and plated. As the samples for the study, we used copper-coated aluminum buses with a rectangular cross section. The coating was sputtered or plated. The buses were used as one of the electrodes. The other electrode was manufactured using M1E copper. It had the shape of a cylinder with a spherical or cone-type butt end. The contacts were plated with a thin silver layer to reduce the effect of weakly conducting films.

The experiments on the layered electrodes were performed using the same experimental equipment and similar techniques as those used for testing of the