NUMERICAL SIMULATION OF THERMAL CONDITION OF A LOW CURRENT ELECTRIC CONTACT

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Abstract. Electrical contacts may include various sub-systems or wiring harness connected via detachable connectors which depend on physical contacts for the electrical connectivity. Electrical contacts range from high, medium to low current depending on their usage. However, in the real-life condition, electrical contacts characteristics, especially at the interface, undergoes a gradual change which can be due to corrosion, temperature variation, aging, strained harnesses, discontinuities induced by vibration etc. These changes introduce additional parasitic circuits in the system. Moreover, in some cases where the contact resistance increases due to electrical loses, the local temperature may increase, thereby accelerating contact degradation. This paper presents a numerical analysis on the variation of temperature of a simple low current contact model having a thin oxide film layer at the interface which serves as the ageing factor using finite element method (FEM).

1. INTRODUCTION

Low current electrical contacts are widely used in automotive, consumer electronics, aerospace and medical applications, amongst numerous engineering fields. Their main function is to close an electrical circuit securely transporting current throughout the contact surface [1]. Because electrical contact is a current path, it produces heat through Joule-Lenz effect and undergoes stresses of different nature (environmental factors, electrical and mechanical factors) etc. [1-2]. It is very important for electrical contacts to possess high resistance to withstand different nature of stresses and to have as large as possible thermal, chemical and electrodynamics stability [3]. Contact resistance is the major source of heat generation; studies have shown that its calculation is approximate to the accuracy of electrical contacts' thermal simulation [4]. Temperature is an important variable to take note of when dealing with electrical contacts. Higher temperature values usually lead to stress relaxation, which reduces contact force. Reduced contact force in turn, produces higher contact resistance, which opposes electrical current and may eventually lead to an open circuit due to deterioration [4-5]. Operating temperature in electrical contacts has three components. Temperature of the surrounding (ambient temperature), temperature rise due to contact resistance of the contact interface and temperature rise due to bulk resistance of the contact material used.

The material often used for electrical contacts is copper due to its good thermal and electrical conductivity but due to its reduced elasticity and low mechanical properties, copper is usually used as an alloy (CuAg, CuMg) etc. According to IEC 60512-2-2a standards, a measurement of contact resistance at 100 mA maximum and open circuit voltage of 20 mV maximum should assure performance at any lower level of current.

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2. ELECTRIC CONTACT DEGRADATION

Talking about the degradation of electrical contacts, studies have shown that the three main important sources affecting the normal functionality of electrical contacts are: fretting, corrosion and the phenomenon coupled with the current flowing.

2.1 Fretting in electric contacts

Fretting as a factor responsible for the deterioration of electrical contacts has posed a great threat to the normal function of contacts in many engineering applications. Fretting is a phenomenon whereby the surface of contacting bodies wears off due to mechanical disturbances such as vibrations (small oscillatory movement), sliding etc. Fretting can have dangerous repercussions for the normal operation of electrical contacts like degrading the surface layer quality producing increased coarseness and micro-pits which reduces the contact force of electrical contacts. Especially alarming is the damaged caused by cracking as it usually goes undetected until the component ruptures completely.

2.2 Corrosion

Corrosion is regarded as one of the most important factors in the degradation process of metal-to-metal contact. It is a process whereby metals in manufactured states return to their natural oxidation states. In other words, corrosion deteriorates materials by chemical reaction with their environment (fig.1). Corrosion process is a reduction-oxidation reaction in which the metal gets oxidized by its surroundings, often the oxygen in the air. Corrosion also occurs in regions/atmosphere where the temperature is high by deforming the protective contacts housing and affecting the alignment of electric contacts. In most cases, metals corrode on contact with water/moisture in the air, oils, aggressive metal polishes, ammonia gas, acid, bases, salt, gases containing sulfur etc. [6-7]

Fig.1 Corroded connector terminals. [8]

2.3 Temperature

The current flowing through contact interface can lead to an increase in temperature of the contact zone especially in cases where the current density is high making it difficult for current to be transferred through to small conducting area. In automotive industry electrical connectors are used in engine compartments and often they are closer to the engine (such as sensor connectors) and are exposed to temperature of 150 ◦C [12]. Swingler et al. [13] have also reported that automobile connectors can reach several high temperature regimes which are grouped in the following classes: 85 ◦C, 105 ◦C, 125 ◦C and 155 ◦C. At higher temperatures, all contact degradation mechanisms may become more severe. This included higher wear because with higher temperature the chemical oxidation and other reaction are faster. For example, Lee et al. [14] show that at elevated temperature, the rate of oxidation of tin contact has an important increase.

3. **NUMERICAL SIMULATION**

The investigated problem is that of a simple electric copper contact located in air (fig. 2). A low DC current of density $\boldsymbol{j}$ is injected by contact terminals and the distribution of electric field and temperature are calculated using the finite element method (FEM) and COMSOL Multiphysics software. The temperature variation study was based on a 3-D thermal-electrical coupled finite element simulation.

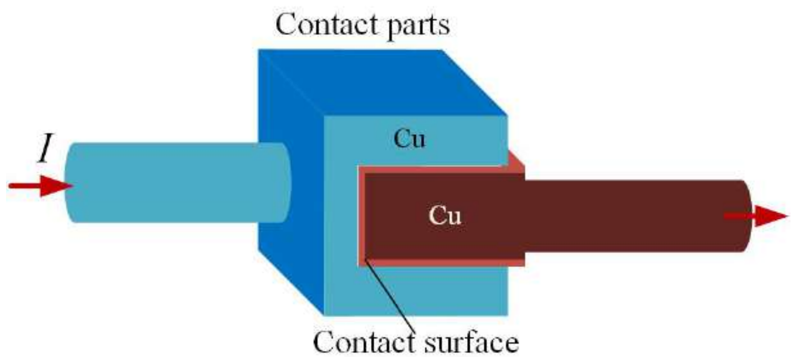


Fig. 2. Schematic view of electric contact.

3.1 Physical model

Analysis of electrical contact temperature variation is very complex in the sense that it involves many influencing factors such as the current, contact force, environmental condition, thermal and electrical characteristics of the material, dimension of the contact etc. One of the most important aspect which is taken into account in this study is that the contact surfaces of an electric contact are not ideally smooth. They are rough and there is a reduction in the real area of contact between two contacting surfaces because they come in contact through peaks/asperities as shown in fig. 3. Moreover, as mentioned above, the contact state is influenced by corrosion, mechanical vibration etc. which can produce an important change of contact resistance. Therefore, in the proposed physical model it is assumed that between the two metal parts of the contact there is a discontinuous layer (for example, a metal oxide layer) with lower electric conductivity than that of copper conductivity through which the electrical current flows.

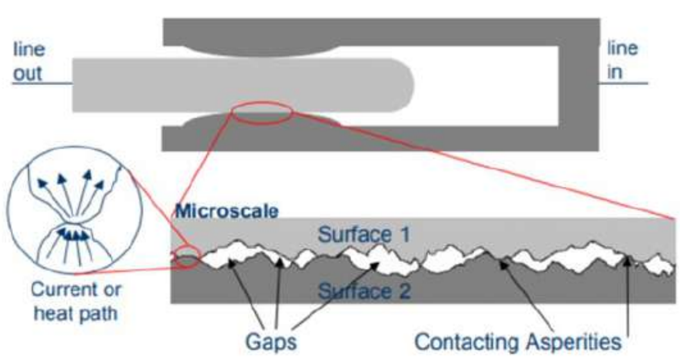
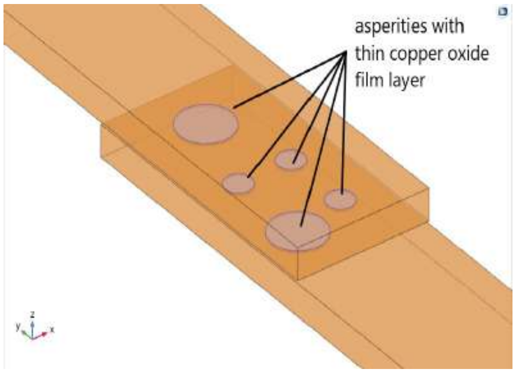


Fig. 3. Schematic view of the surface contact between two metals. [11]

In order to simplify the problem, only half of the contact shown in figure 2 is considered. In this way, the analysis is limited to investigating the contact of two metallic strips between which there is a discontinuous layer of copper oxide with different values of electric conductivity (fig. 4). Both metallic strips (strip 1 and strip 2) have the following dimensions: length l =10 mm, width w =1mm and height h = 0.2 mm. The asperities (peaks) have a cylindric shape with radius r_1 = 0.2 mm and r_2 = 0.1 mm respectively and the height h = 0.01mm. The thin oxide film has a thickness between 10 μm and 50 μm.



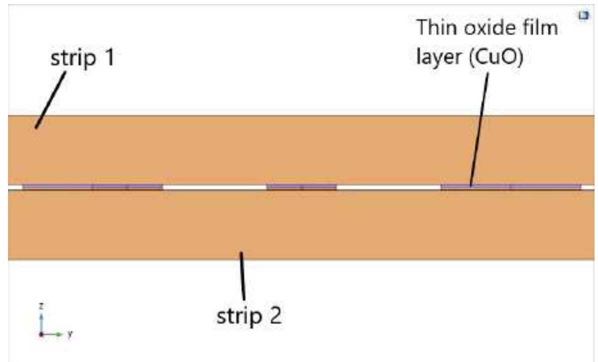


Fig.4. Geometrical model with copper oxide asperities.

3.2 Mathematical model

The multiphysics analysis consists of an electromagnetic and thermal problem. For the electromagnetic problem it is considered that the stationary electro-kinetic regime with an imposed constant electric current of density $\boldsymbol{j}$ flowing through the contact (the thin discontinuous layer located between the two copper strips). The fundamental equations of the problem are:

$$\operatorname{div} \boldsymbol{j} = \boldsymbol{0}, \tag{1}$$

$$\operatorname{rot} \boldsymbol{E} = \boldsymbol{0}, \tag{2}$$

$$\boldsymbol{j} = \sigma \cdot \boldsymbol{E}, \tag{3}$$

which are the particular forms of the charge conservation law, electromagnetic induction law and electric conduction law. $\boldsymbol{E}$ is the electric field strength and σ is the electric conductivity supposed to be a constant (does not vary with temperature). The electric field strength $\boldsymbol{E}$ can be calculated as a function of electric potential V:

$$\boldsymbol{E} = -\operatorname{grad} V. \tag{4}$$

The boundary conditions for equations (1) are:

- Continuity $\boldsymbol{n}\cdot(\boldsymbol{j}_1-\boldsymbol{j}_2) = 0$ which specifies that the normal components of the electric current are continuous across the interior boundary $\boldsymbol{j}_1$ and $\boldsymbol{j}_2$ are the current density on opposite sides of the contact layer located between the two metallic strips.
- Electric insulation $\boldsymbol{n}\cdot\boldsymbol{j} = 0$ on all surfaces except those of the contact areas. This specifies that no current flows across the boundary. This boundary condition is also applicable at symmetric boundaries where the electric potential is known to be symmetric with respect to the boundary.

The volume density of the electrical losses (Joule losses) that correspond to the electric current flow through the metal strips and the contact layer are calculated using the law of energy transformation:

$$p = \boldsymbol{j} \cdot \boldsymbol{E} = \sigma \boldsymbol{E}^2. \tag{5}$$

The thermal problem concerns the heating of the contact due to the resistive losses. In the proposed model the contact is placed in an air-filled box having the boundary condition set at ambient temperature $T_0 = 20$ ^{o}C. The convection and radiations mechanisms are neglected and only the steady state thermal conduction will be considered. Therefore, the heat equation is:

$$Q = \nabla \psi, \tag{6}$$

where Q is the heat source (equation (5)) and ψ is the heat flux given by Fourier law

$$\psi = -\lambda \cdot \nabla T, \tag{7}$$

where T is absolute temperature and λ is thermal conductivity which is supposed constant (does not change with temperature). Initial condition of equation (7) is $T = T_0$ in each point of the computation domain. Also, continuity conditions (constant heat flux) are imposed on each boundary between two different regions (subdomains) j and k:

$$\boldsymbol{n} \cdot (\lambda_j \nabla T_j - \lambda_k \nabla T_k) = 0, \tag{8}$$

where λ_j and λ_k are thermal conductivity in j and k subdomains.

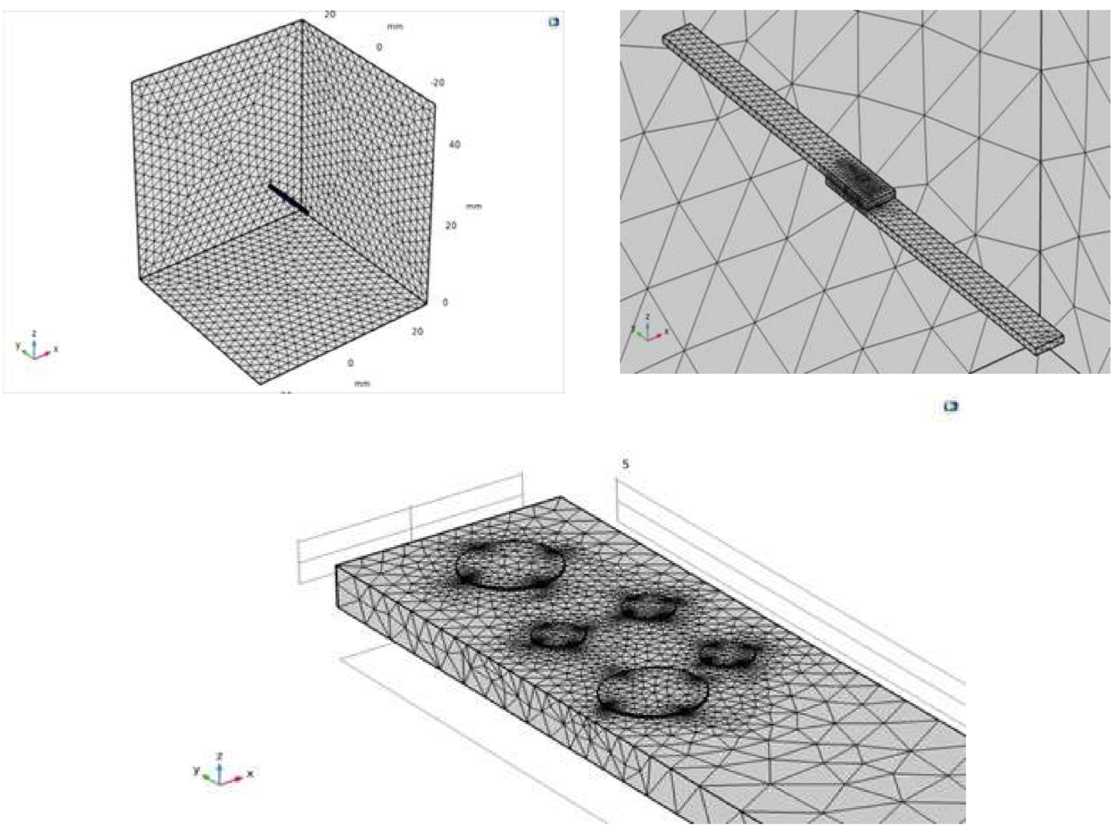


Fig.5. Discretization of the computational domain.

3.3 Numerical model

The two coupled problems were solved using the finite element method (FEM) and COMSOL Multiphysics software. As shown in fig.4 the two copper strips come in contact through several cylindrical asperities (peaks). To do a numerical analysis on something close to a real electrical contact, a simple model with cylindrical asperities and an oxide film layer at the interface as shown in fig.4 is considered. The analysis is done with a continuous current flowing through the conductors. The idea is to analyze the temperature variation of the contact zone for different values of electric conductivity of the oxide film layer. Figure 5 shows the discretization of the computation domain.

4. RESULTS AND DISCUSSIONS

The computed temperature distribution for j = $2.5 \cdot 10^6$ A/m^2, λ_{Cu}= 400 W/(m·K), λ_{CuO}=33 W/(m·K), λ_{air}=0.0252 W/(m·K), and T_0 = 20 ^{o}C is presented in fig. 6. The steady state is reached after t = 200 s. As seen in fig. 6 the highest temperature 28.8 ^{o}C is reached at the mating point/contact zone due to constriction of current lines and the coverage of the surface with disturbing copper oxide films.

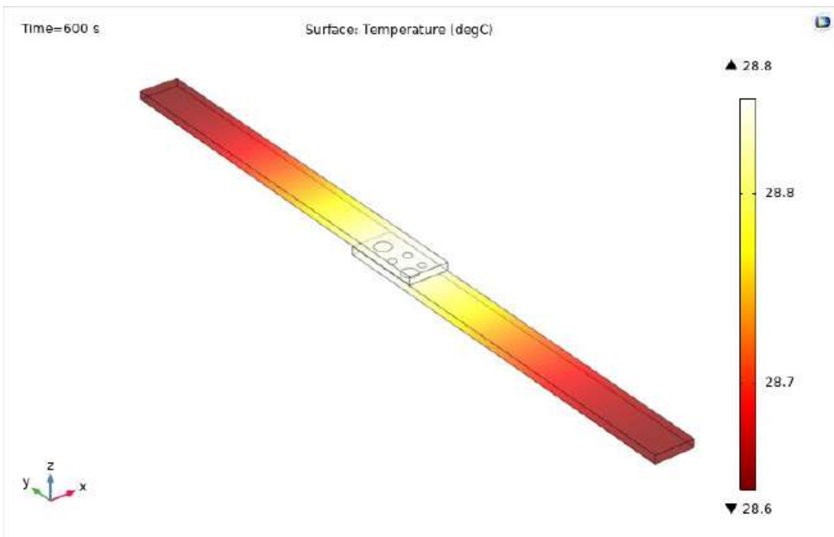
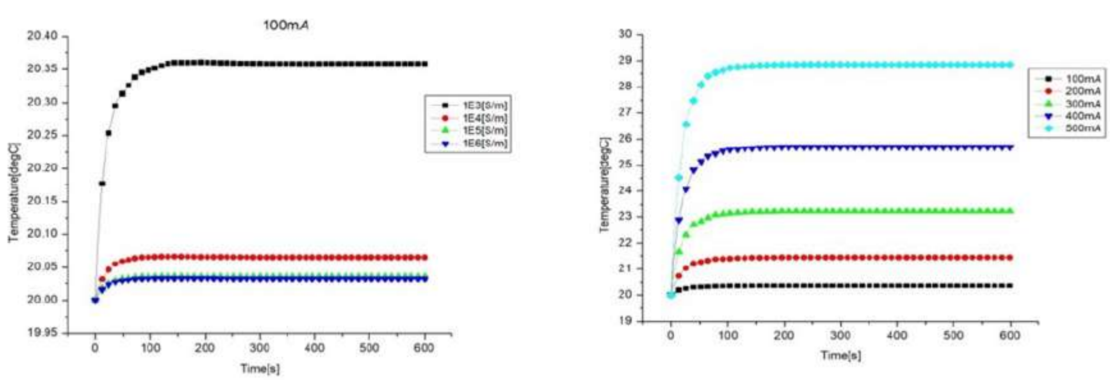


Fig.6. Temperature distribution in the contact zone and cooper strips.



a) *b*)

Fig.7. Temperature variation with time obtained by a point measurement at the interface of the overlapping conductors for: *a*) Different values of electric conductivity of the oxide film and an injected current of 100 mA; *b*) Different values of injected current.

Figure 7 shows the variation of temperature with time for T_0 = 20 °C and different values of electric conductivity of oxide contact layer (*a*) and several values of injected current (*b*). It can be seen that when the values of the electrical conductivities of thin oxide film are between 10^3 and 10^6 S/m (which is less than that of the two copper conductors $\sigma_{Cu} = 5.96 \cdot 10^7$ S/m) as expected, the lower the electrical conductivity of the thin oxide film, the higher the temperature. The steady state is reached after a time *t* = 200 s. Figure (7b) shows the variation of the contact temperature rise as the current increases for $\sigma_{CuO} = 10^3$ S/m. The result shows that if the current increase from 100 mA to 300 mA, the temperature increases from about 20.5 °C to 23.3 °C and for 500 mA the temperature becomes 28.8 °C. Variation of contact temperature as a function of injected current is presented on fig. 8. Once again, as expected *T* varies with the square of the current as the formula of resistive losses in conductors indicates.

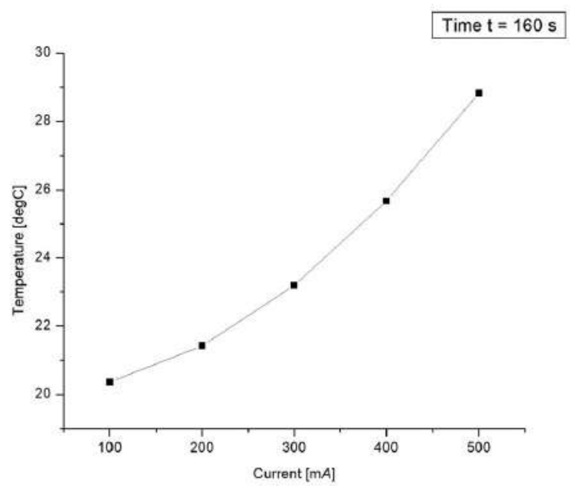


Fig. 8. Variation of steady state temperature as a function of injected current.

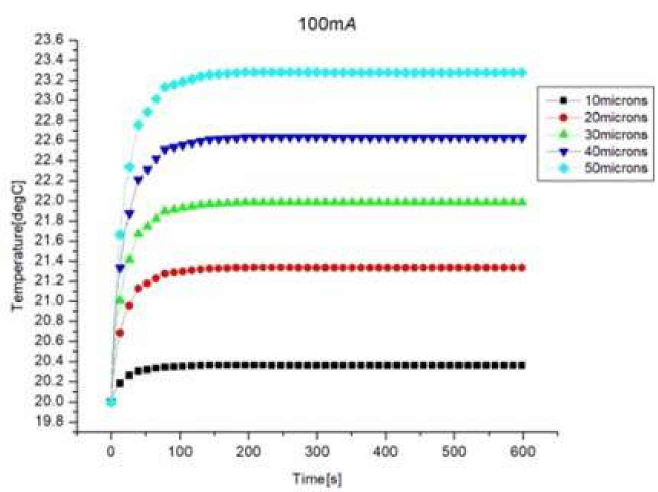


Fig.9. Temperature variation as a function of the oxide film thickness at the contact interface.

Figure 9 shows the variation of the contact temperature as the thickness of the thin oxide film layer at the interface increases. As expected, according to the results, the contact temperature rises with the oxide film thickness. The more the oxide films form at the interface, they tend to act as a low electric conductivity material thereby, increasing the resistance and the temperature rise at the interface and further the deterioration of the contact. For an injected current of 100 mA the results show that when the oxide film thickness increases from 10 μm to 40 μm, the temperature increases from 20.2 ^{o}C to 22.5 ^{o}C and for a thickness of 50 μm the temperature becomes 23.3 ^{o}C.

4. CONCLUSION

This paper presents a numerical study regarding the temperature variation of a low current electrical contact affected by surface oxidation and considering in a simplified way the microscopic asperities that flow the current between the contact conductors. The proposed model requires, on the one hand, solving the electrical problem regarding the distribution of electric current in the contact volume and, on the other hand, calculating the temperature field (solving the thermal problem). The two problems are related by the fact that the source term of the heat equation is the resistive electrical losses calculated in the electrical problem.

Although the proposed model is a simplified one in which, among other simplifying hypotheses, the thermal conductivity is supposed constant (does not vary with temperature), the obtained numerical results indicate that temperature increases when the electrical conductivity of the thin oxide layer decreases, the thickness of the oxide film increases or the electric current through the contact also increases. Even if apparently the contact temperature rise is not important (being only a few degrees Celsius), it must be emphasized that temperature is one of the factors that favor the degradation of contacts.

The presented model will be developed both from the point of view of geometry and from the point of view of the considered hypotheses (variation of metallic conductivity with temperature, different electric conductivity for contact asperities etc.).

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