An Experimentally Validated 3D Multi-physics Multi-scale Model for Electrical Interconnects

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Abstract—The paper presents an improved three-dimensional mechanical-electrical-thermal coupled model for electrical interconnects. It combines a FEM mechanical analysis with a Cell Method approach for the thermal-electrical analysis that is based on a mortar type Domain Decomposition Method. The roughness of the contact surfaces is taken into account by means of a statistical formulation that can easily embedded into the Cell Method model. The statistical parameters depend on the apparent contact pressure and surface, which are assessed with the FEM analysis. The model has been validated both numerically and experimentally on a classical sphere-plane contact problem, where all relevant physical quantities have been determined and compared.

I. Introduction

A major issue in designing electrical interconnects consists in assessing contact resistance and temperature rise due to the localized Joule heating at the contact interfaces, which call for numerical analysis tools able to simulate multiscale and fully coupled electrical, thermal, and mechanical effects. A novel domain decomposition method (DDM) for analyzing three-dimensional (3D) electro-thermal contact problems has been recently proposed [1]. This DDM allows the computational domain to be split into subdomains (e.g. contacting members) and continuity between them is enforced by dual Lagrange multipliers defined on the so-called mortar surface. Field problems inside the bulk regions are discretized with the Cell Method (CM) thus resorting directly to algebraic equations. Voltage and temperature jumps across the contact are modeled with constitutive equations accounting for microscopic contact effects. The DDM is here combined with a FEM code in order to model contact mechanics as well.

II. Contact Physics Model

Conducting metals used in electrical interconnectors typically undergo a locally plastic deformation. Therefore a realistic estimate of the stress state around contact interfaces requires a non-linear elastoplastic model. The yield surface can be estimated by using the Von Mises isotropic yield criterion [2]:

$$\sqrt{3}\cdot\overline{\sigma} - Y\left(\underline{k}\right) = 0 \tag{1}$$

where $\underline{k}$ the kinematic hardening parameter, in the case of one-dimensional analysis $Y(\underline{k})$ equals the yield stress, and:

$$\overline{\sigma} = \sqrt{(\sigma_x^2 + \sigma_y^2 + \sigma_z^2)/2 + \tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2} \tag{2}$$

being σ the stress tensor. Fig. 1 shows the stress-strain law adopted to simulate kinematic hardening in the case of brass material.

The FEM code simulates the elastoplastic deformation of members pressed together. In the case of non-planar contacting surfaces such analysis provides the shape and size of the apparent (macroscopic) contact area A_a and pressure p [3]. The contact search algorithm relies on the Augmented Lagrangian formulation described in [4], whereas the mechanical analysis in bulk regions is performed under the small strain assumption.

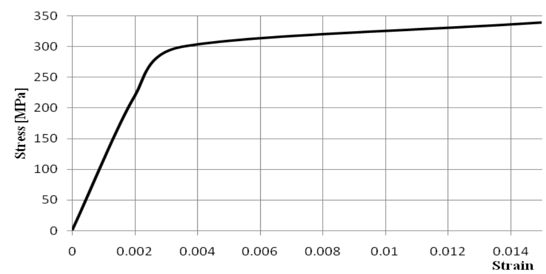

Fig. 1. Material stress-strain constitutive law.

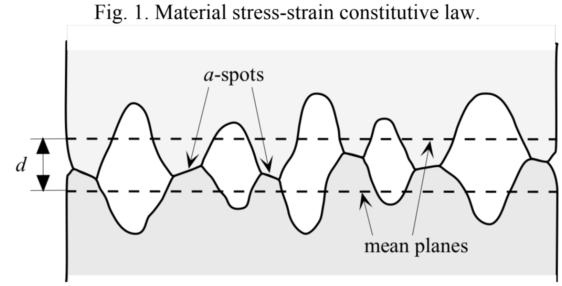

Fig. 2. Microscopic contacts due to the surface roughness: The distance d between the mean planes depends on the applied force F.

According to Holm's theory described in [5] contacts occur in a number n_c of small surfaces called *a*-spots so that the actual contact area A_c is much smaller than A_a (Fig. 2). Field lines squeezes through *a*-spots causing a local increase of resistivity, producing the *constriction resistance*. The total contact resistance can be estimated by means of a statistical approach that bridges the microscopic contact physics to the meso-scale discretized model [6][7], and defines the total constriction resistance as a function of parameters such as surface roughness, material hardness, and pressure p.

By assuming a Gaussian distribution of micro-contacts and a locally plastic deformation, the mean dimensionless separation gap $\xi = d/d_{max}$ can be expressed as:

$$\xi = \sqrt{2}\ erfc^{-1}\left[\frac{2p}{c_1(1.62r/m)^{c_2}}\right]^{\frac{1}{1+0.071c_2}} \tag{3}$$

where r is the rms roughness, m is the mean absolute slope and c_1, c_2 are correlation coefficients. The constriction electrical conductivity (and similarly the thermal one) is then computed by means of:

$$\sigma_c = \frac{m\sigma}{2\sqrt{2\pi}\ r}\frac{exp(-\xi^2/2)}{(1-\sqrt{p/H})^{1.5}} \tag{4}$$

where H is Mayer's indentation hardness. The total constriction resistance so obtained is added with a film resistance accounting for additional ohmic losses due to surface contamination.

III. Numerical model

The contact model is embedded into the constitutive relationships of the DDM formulation. According to the CM, in order to introduce Lagrange multipliers a new reference frame must be defined, namely the mortar surface, that in our model is generated from the discretized surfaces of contacting members. Electric potentials and temperature jumps at the contact interface are due to the contact resistances obtained from (4), which are included in the constitutive matrices M_{σ_C} and M_{λ_C}. Coupled electric and thermal equations of bulk and contact regions are assembled in the following non-linear system, that extends the contact coupled model previously developed [1]:

$$\begin{pmatrix} G^T M_\sigma G & O & -Q^T P^T & O \\ O & G^T M_\lambda G & O & -Q^T P^T \\ PQ & O & M_{\sigma_C^{-1}} & O \\ O & PQ & O & M_{\lambda_C^{-1}} \end{pmatrix} \begin{pmatrix} v \\ \theta \\ j_m \\ q_m \end{pmatrix} = \begin{pmatrix} j_s \\ w \\ 0 \\ w_m \end{pmatrix} \tag{5}$$

where v is the electric potential array, θ the temperature array. Eq. (5) is solved iteratively after having eliminated Lagrange multipliers, i.e. currents $\boldsymbol{j}_m$ and heat fluxes q_m.

IV. Experimental validation

The numerical method has been tested both numerically and experimentally on a sphere-plane contact geometry [3]. Fig. 3 shows the test set-up used in the experiments: cylindrical copper or brass specimens with members of the same diameter (9 cm) have been used. As a first step, specimen surfaces have undergone roughness profile measurements (Fig. 4), aimed at determining the statistical parameters required in the contact model described by (3) and (4): r_{al}=0.171 µm, m_{al}=1.313, r_{br}=0.158 µm, m_{br}=1.254.

The mechanical load F has been increased step after step and a current I ranging from 0 to 1 kA has been applied at each step. At every F-I condition the steady state temperature $\theta(P,t)$ and electric potential $v(P,t)$ distributions are measured along the member surfaces, together with integral quantities: F, I, deformation δ, and contact voltage U_C.

Once the correlation between F-I and $\theta(P,t)$ and $v(P,t)$ distributions has been assessed experimentally, they have been compared with results computed with the numerical model. Finally measured and computed field distributions have been checked against the Kohlrausch's fundamental law, that provides the contact voltage drop U_C as a function of the maximum temperature θ_m at the contact interfaces and bulk temperature θ_o:

$$U_C = 2\sqrt{L\ (\theta_m^2 - \theta_o^2)} \tag{6}$$

A thorough discussion of the 3D multi-physic numerical analysis with its last improvements and experimental validation will be presented in the full paper.

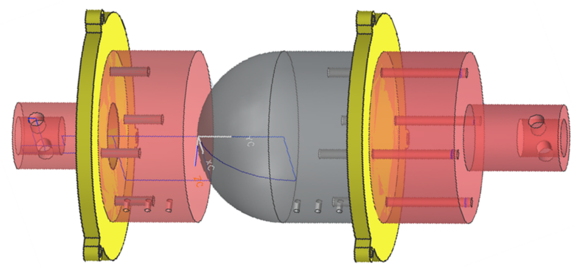

Fig. 3. Sphere-plane contact geometry used for the experimental validation.

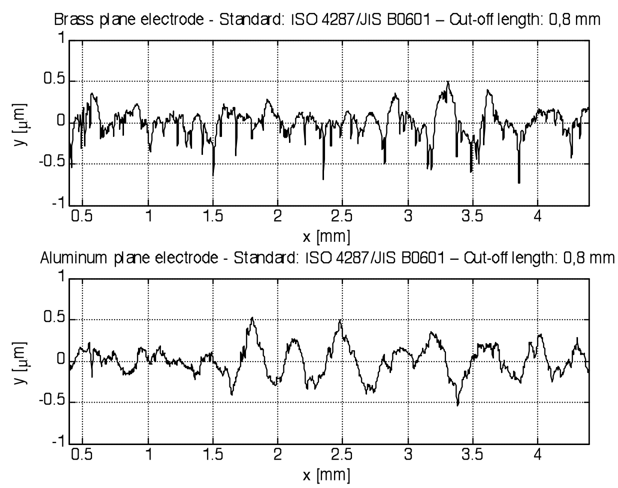

Fig. 4. Measured roughness profiles of the contact surfaces in the case of aluminum (upper) and brass (lower) specimens.

V. References

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