A modelling technique for 3D multi-scale heat transfer analysis : Application to flexible printed circuit microconnectors.

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Abstract

The paper presents an advanced modelling technique for 3D multi-scale thermal analysis and thermal design of Microsystems and, especially, flexible printed microcircuit (FPC). The technique is based on an original approach consisting to transform the 3D heat conduction problem in the combination of two heat conduction problems, basically 1D and 2D. The model can provide on one hand the 3D temperature distributions in steady state conditions and on the other hand the optimal electrical current distribution achieving the lowest temperature level. The model does not require a mesh and it lead to a reduce CPU time. The model performs an efficient design tool. Results are in very good accordance with 3D Finite Element simulations and with experiments. In addition a thermal analyses have been performed.

Keywords : *Compact model, thermal modelling, microconnectors.*

1. INTRODUCTION

Designed originally to replace wiring harnesses, Flexible Printed Circuits microconnectors (FPC) achieve electrical connection between different parts of electronic equipments. FPC connectors are basically composed of thin copper lines of various shapes and sizes, forming a complex circuit pattern integrated in an insulating polymer sheet. Metal lines under consideration have a wide range of dimensions comprised from several micrometers to few centimeters.

From their nature, FPC strongly contribute to size and weight reductions because of their ability to withstand bending and twisting. It is the reason why FPC micro-connectors are intensively used in electronic products and parts (video cameras, mobile phones, computer, sensors, and microsystems…). Nowadays, more and more applications in automotive and aerospace require interconnect systems of high density (especially electrical micro-connectors made with FPC) working in harsh environment. These systems have to be able to supply many input/output signals and high current levels. In the future, miniaturisation and increase of power densities pose crucial thermal questions for the next generation of interconnect systems.

Standard dimensions of FPC are a few centimeters of length and width. Metal lines thickness goes from 20 to 50 µm, and his width is some tens of micrometers to some millimeters. Density of electrical currents is between 10^6 and 10^8 $A.m^{-2}$. The thickness of polymer on both sides of the metal lines is 50 to 100 µm. The two ends of FPC are usually attached one, on a external connector, and the other, on electronic module, maintained at different temperatures giving different boundary conditions at the two ends of the FPC.

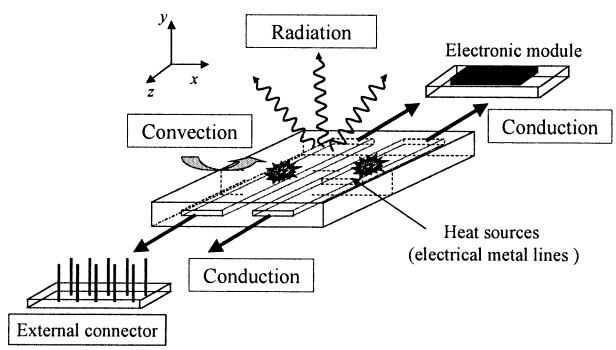

Figure 1 : Thermal phenomena in FPC microconnectors

The paper presents an advanced modelling technique for 3D multi-scale thermal analysis of microsystems and especially flexible printed microcircuit (FPC). The model provides 3D temperature distributions in steady state conditions. Principle of the model is described. The thermal model has been validated from experiments and numerical simulations in various working conditions.

Some application of the model are present to find the optimal electrical current distribution achieving the lowest temperature.

2. PRINCIPE OF THE MODEL

The modelling technique is based on an original resolution of the three-dimensional heat conduction problem. In this resolution, one considers that each metal line is a fin and heat transfer and influence between the metal lines occur exclusively in cross section of the interconnection system.

The heat conduction equation, established for each line, leads to the resolution of a monodimensional problem of conduction (1D) needing the expression of the net heat flux Φj exchanged from the line j considered, with the other lines, and with the surrounding medium. In this problem, cross-sections of each metal line are assumed isothermal.

The net heat flux Φj is a function of the temperature of each line. The calculation of Φj requires the resolution of a two-dimensional problem of conduction (2D).

In the 1 D problem the temperature $\theta_j(z)$ of each line j (j=1,..,J), satisfies the following differential equation given by the energy balance :

$$\begin{aligned} &\frac{d^2\theta_1(z)}{dz^2} - \frac{\Phi_1(z)}{\lambda_c e_c} = -\frac{P_1}{\lambda_c} \\ &\quad\vdots \\ &\frac{d^2\theta_j(z)}{dz^2} - \frac{\Phi_j(z)}{\lambda_c e_c} = -\frac{P_j}{\lambda_c} \\ &\quad\vdots \\ &\frac{d^2\theta_J(z)}{dz^2} - \frac{\Phi_J(z)}{\lambda_c e_c} = -\frac{P_J}{\lambda_c} \end{aligned} \tag{1}$$

P_j : energy generation rate per unit volume of line j.
$\theta_j(z)$: temperature of line j, with $\theta_j(z)=T_j(z)-Ta$.
$\Phi_j(z)$: net heat flux.

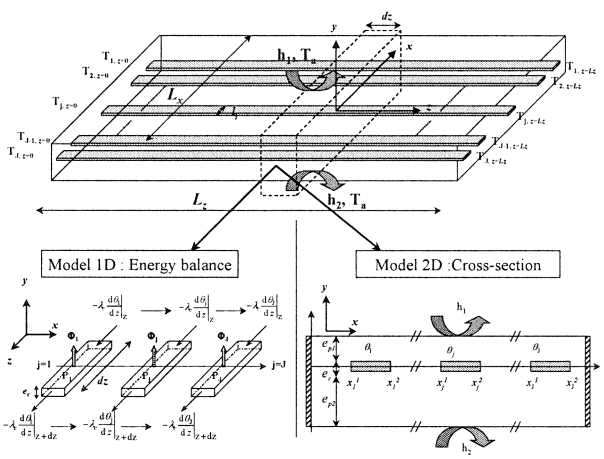

Figure 2 : Principe of the model

The net heat flux can be written as the following form :

$$\Phi_j(z)=c_{j,1}\theta_1(z)+c_{j,2}\theta_2(z)+.....+c_{j,j}\theta_j(z)+...+c_{j,J}\theta_J(z) \tag{2}$$

where $c_{i,j}$ are the set of influence coefficients deduced from the decomposition of Φ_j in two terms [1]. Coefficients $c_{i,j}$ are given by :

$$\begin{aligned} &c_{j,i}=k_{j,i} && \text{if } i\neq j\text{-}1,\ j,\ j\text{+}1 \\ &c_{j,i}=k_{j,j-1}\frac{\lambda_p}{x_j^+-x_{j-1}^-}\cdot\frac{e_c}{l_j} && \text{if } i=j\text{-}1 \\ &c_{j,i}=k_{j,j}+\left(\frac{\lambda_p}{x_j^+-x_{j-1}^-}+\frac{\lambda_p}{x_{j+1}^+-x_j^-}\right)\frac{e_c}{l_j} && \text{if } i=j \\ &c_{j,i}=k_{j,j-1}\frac{\lambda_p}{x_j^+-x_{j-1}^-}\cdot\frac{e_c}{l_j} && \text{if } i=j\text{+}1 \end{aligned} \tag{3}$$

Calculation $k_{i,j}$ coefficients is not trivial and was carried out with the truncated method series [2]-[4]. It can be set that $k_{i,j}$ describes simultaneously, the interaction between each metal line and the surrounding medium.

The total number of influence coefficients is $J*J$. Let us combine equations (1) and (2), then we obtain a system of differential equations which can be written as :

$$\frac{d^2[\theta]}{dz^2} - [G][\theta]=[Q] \tag{4}$$

The coefficients of matrice [G] are given by :

$$g_{i,j}=\frac{c_{i,j}}{\lambda_c e_c} \tag{5}$$

System (3) is solved by diagonalization and becomes :

$$\frac{d_2[\theta_0]}{dz_2} - [G_0][\theta_0]=[Q_0] \tag{6}$$

$[G_0]=[P]^{-1}[G]\ [P]$. $[G_0]$ is a diagonal matrice composed of the eigenvalues k_j of [G]. [P] is a matrice composed with the eigenvector of the matrix [G].

$$[Q_0]=[P]^{-1}[Q] \quad \text{and} \quad [\theta_0]=[P]^{-1}[\theta] \tag{7}$$

The solution of the system (4) is then given by :

$$\begin{aligned} &\theta_{0j}(z)=\Omega_j ch(m_j*(z-L_z))+\Lambda_j sh(m_j*(z-L_z))-\frac{Q_{0j}}{m_j^2} && \text{if } k_j>0 \\ &\theta_{0j}(z)=\Omega_j \cos(m_j*(z-L_z))+\Lambda_j \sin(m_j*(z-L_z))-\frac{Q_{0j}}{m_j^2} && \text{if } k_j<0 \end{aligned} \tag{8}$$

L_z is the length of the flexible and $m_j=\sqrt{|k_j|}$. Constants Ω_j and Λ_j are determined from the boundary conditions $\theta_{0j}(L_z)$ and $\theta_{0j}(0)$ given by :

$$\begin{cases} [\theta_0]_{z=0}=[P][\theta]_{z=0} \\ [\theta_0]_{z=Lz}=[P][\theta]_{z=Lz} \end{cases} \tag{9}$$

Finally, temperature distributions of the metal lines are obtained from the following relation :

$$[\theta]=[P]^{-1}[\theta_0] \quad (10)$$

3. VALIDATION OF THE MODEL

3.1 Numerical validation.

The temperature distribution calculated from the analytical model are compared with those given by a 3D Finite Element model on figure 3. The cross section geometric of the FPC is given on figure 2 (L_z=100 mm, e_{p1}= e_{p2}=50 µm, h_1= h_2 =10 W.m^{-2}.K^{-1}). The heat volume dissipation is 3 10^7 W.m^{-3} in the third and fifth metal lines.

Results are in very good accordance, even for the no symmetrical FPC. Temperature difference between the two methods does not exceed 1%. Moreover, the finite Element model confirms one major assumption of the model: cross sections of metal line are isothermal.

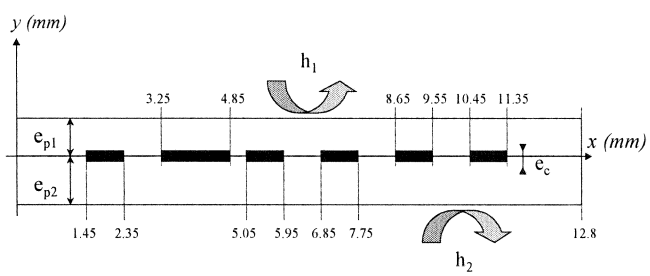

Figure 2 : Cross section of the 6 metal lines FPC.

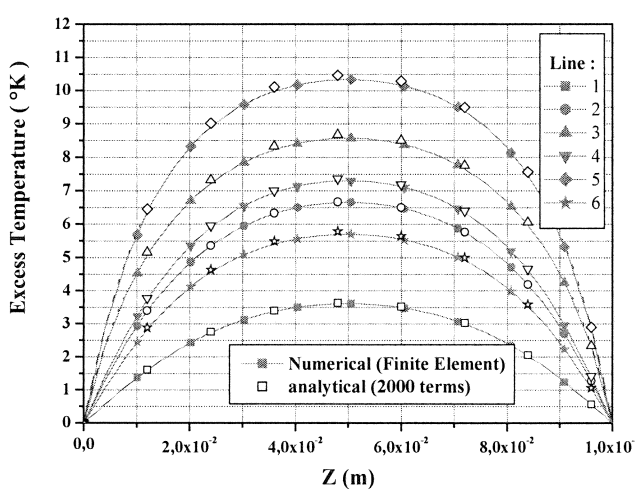

Figure 3 : Comparison between numerical and analytical results

3.2 Experimental validation.

Experiments have been conducted on a FPC of 93 mm in length, 30 mm in width and a 145 µm thickness. The FPC is composed of 22 thin copper lines with a thickness of 35 µm, width of line 2 to 21 is 0.9 mm and width of line 1 and 22 is 1.4mm. The thickness of the polymer sheet is 55 µm on both sides of copper. Distance between two metal lines is 250 µm. The experimental set up is composed of the FPC, including temperature sensors set in an isothermal enclosure [1]. Nine micro-thermocouples (diameter : 12 µm) were distributed on three metal lines (number 11, 12, 13) located side by side in the middle of the 19 others. Metal lines 11,12,13 are supply by a set of electrical current.

We present figure 4 one comparison obtained from this experimental validation. In all working conditions, the difference between the experimental and calculated temperatures does not exceed 3 % for the hot spot at the middle of the FPC. Heat transfer h_1= h_2 are taken into account in the analytical model by using [3].

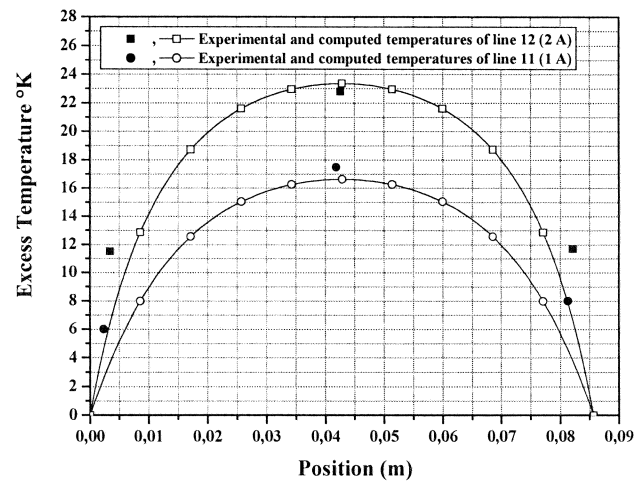

Figure 4 : Comparison between experimental and analytical results.

4. THERMALS ANALYSIS AND OPTIMISATION

We present a thermal analysis and some examples of optimisation on a 22 lines FPC described in §3.2. Heat transfer coefficients used are h_1 = h_2 = 15 W.m^{-2}.K^{-1}.

4.1 Thermal analysis

The figure 5 and 6 illustrate some examples of temperature distribution and fraction of the total power removed by conduction and by convection/radiation from each metal line. A power of 660 mW is dissipated in the metal lines 7, 12 and 17 (I_{11}= I_{12}= I_{13} = 2 A).

Thermal analysis shows that the temperature rises are important in all directions even in passive lines in wich power is not generated. About 60 % of the total power is removed by convection and radiation. It appears that passive lines act like heat sinks and play consequently an essential role on the magnitude of heat removed. In addition, a more homogenous power distribution reduces the temperature level and increases the efficiency of passive lines as heat sinks.

Set	Number of current				Current in metal line number :																				
N°	1 A	2 A	3 A	4 A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	15	4	1	2	**4**	1	**2**	**2**	1	**3**	1	**2**	**2**	1	1	1	1	1	1	1	1	1	1	1	1	**4**
2	15	2	2	4	**4**	**3**	1	1	1	1	1	**4**	1	1	1	1	1	1	**4**	1	1	1	1	**2**	**2**	**4**
3	15	2	4	1	**4**	1	1	1	1	1	**3**	1	1	1	**3**	1	1	1	1	**3**	1	1	**2**	1	**2**	**3**
4	12	0	10	0	**3**	**3**	1	1	**3**	1	**3**	1	1	**3**	1	**3**	1	1	**3**	1	**3**	1	1	**3**	1	**3**

Table 1 : Optimal distribution of a set of electrical current in the 22 metal lines.

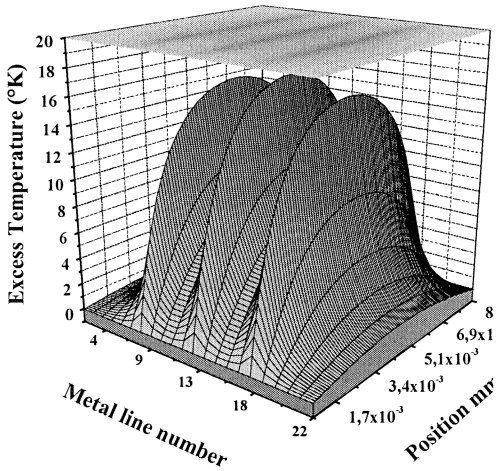

Figure 5 : Temperature distribution of a 22 metal lines FPC, $I_{11}=I_{12}=I_{13}= 2$ A and $h_1=h_2= 15$ W.m^{-2}.K^{-1}.

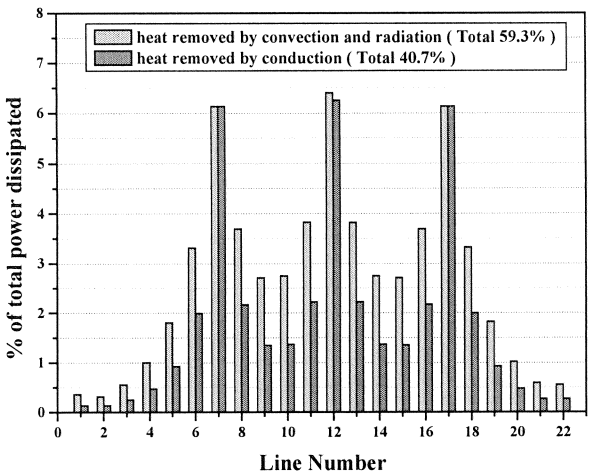

Figure 6 : Fraction of power removed by conduction and convection/radiation.

4.2 Example of Optimisation

The question under consideration is : for a given set of electrical current, what is the optimal current distribution in the 22 metal lines, in order to obtain the lowest maximum temperature?

The sets of treated currents and the results obtained are presented in Table 1. The temperature distribution of the optimal combination of set 1 is presented on figure 7. The number of combinations for each set of current is between 6.10^5 and 6.10^9.

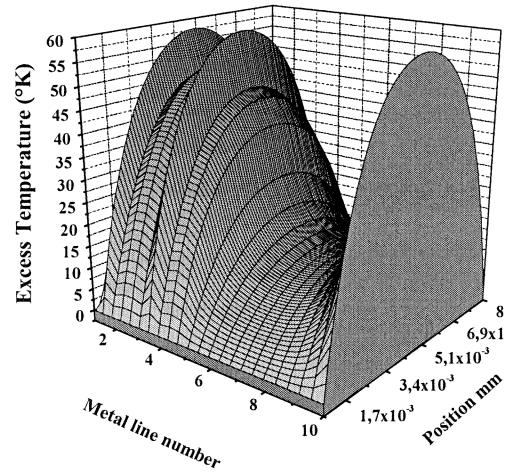

Figure 7 : Temperature distribution for the optimal combination of the set 1.

CONCLUSION

We have presented an advanced modelling technique for 3D multi-scale heat transfer in the Flexible printed circuits. The model has been validated in various working conditions from experiments and numerical simulations.

This model has been used for the thermal analysis of heat transfers in the Flexible printed circuits. It shows that a significant fraction of the power is removed by convection/radiation and that passive lines, in which power is not generated, play an essential role.

The major application of this model is the thermal design of the Flexible printed circuits. In particularly, the model enables to determine optimal electrical current distribution.

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