ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

ANALYSIS OF EFFECTIVE THERMAL CONDUCTIVITY OF PRINTED CIRCUIT BOARDS WITH A SYMMETRICAL OR ASYMMETRICAL HEAT SOURCE

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Abstract. *This work has a main objective to obtain correlations for the effective thermal conductivity of a Printed circuit board (PCB) with a heat source. Numerical solutions of three-dimensional heat conduction equation were used to study variation of the effective thermal conductivity of PCBs with the size and geometric shape of the heat source. These numerical solutions were obtained using the commercial software ANSYS. Solutions were obtained for two, three and four numbers of internal copper layers, and different size components and rectangular and circular geometry of the heat source. It was shown that the effective thermal conductivity of a PCB would be larger than the values given by the one-dimensional effective thermal conductivity model if the heat source on the PCB were smaller than the PCB itself, taking into account the geometry asymmetrical from heat source. The difference was more pronounced for smaller heat source.*

Keywords: *Thermal Conductivity, Effective Thermal Conductivity, Printed Circuit Board, Heat Source, Numerical Simulation*

1. INTRODUCTION

The compression of electronic components has generated problems in maintaining stable systems. These problems are generated due to increased power density dissipated. Part of this energy is dissipated by heat transfer by conduction to the PCB. With increasing power density, the amount of heat that is dissipated through the PCB becomes an important fraction of the total heat dissipated by these devices. The heat generated by the components is conducted to the PCB through their leads and or cases, which in turn dissipates this heat to other components if necessary, and the surrounding environment. This heat transfer depends on the thermal conductivity of the PCB. Manno, 1993 showed the significant impact of the PCB conduction on the maximum board and component temperatures. Shaukatullah and Gaynes, 1994 showed that the thermal performance of surface mount packages was sensitive to the amount of copper in the PCB.

PCBs are complex multi-layer structures in which layers of high thermal conductivity copper are sandwiched between those of low thermal conductivity glass-epoxy. Because of the large difference between the thermal conductivities of copper and glass-epoxy, the thermal conductivity of the PCB, as a whole, is strongly orthotropic. Modeling layers of copper and glass-epoxy of the PCI in a numerical model of an electronic device makes the model very large, generating a long time to calculate each iteration and greater number of iterations for convergence of the governing equations. To overcome this obstacle, PCBs are usually modeled as single objects with parallel (in the plane of the board) and normal (perpendicular to the board) effective thermal conductivities. For Yunus, 1998, the effective parallel and normal thermal conductivities are typically calculated assuming one-dimensional heat conduction through a composite layer, and for Azar and Gralebner, 1996, neglecting the thermal contact resistance between the copper and glass-epoxy layers. For a PCB with N_c, number of copper layers and N_g, number of glass-epoxy layers:

$$k_{p,e} = \frac{\sum_{i=1}^{N_c} k_c t_{c,i} + \sum_{i=1}^{N_g} k_g t_{g,i}}{t} \quad (1)$$

$$k_{n,e} = \frac{t}{\sum_{i=1}^{N_c} \frac{t_{c,i}}{k_c} + \sum_{i=1}^{N_g} \frac{t_{g,i}}{k_g}} \quad (2)$$

Where t is the total thickness of PCB, $t_{c,i}$ and $t_{g,i}$ are the thicknesses of the ith copper and glass-epoxy layers, and k_c and k_g are thermal conductivities of copper and glass-epoxy. This model is called the "one-dimensional effective thermal conductivity" model (k-eff-1D model).

For cases where the component is smaller than the PCI, which is very common in the electronics industry, consider the one-dimensional heat conduction through the board, may result in large errors. Shabany, 2002, showed how the model k-eff-1D may be inaccurate in these situations and he proposed modifications to this model. Shabany suggested the "modified effective thermal conductivity" model (k-eff-mod model), in which the effective parallel and normal thermal conductivity of the PCB model were obtained by an iterative process. This process included two steps. First, numerical solution of the heat conduction equation in the detailed PCB geometry was used to obtain the maximum source temperature and the maximum board temperature opposite the source. Then, numerical solution of the heat conduction equation in the orthotropic model of the same PCB (the second model mentioned above) was obtained with a given set of parallel and normal thermal conductivities. These thermal conductivities were iteratively corrected such that the maximum heat source temperature and the maximum PCB temperature opposite the heat source were predicted within 1% of the values predicted by the detailed PCB simulation. The result was to obtain two equations correlating the thermal conductivity (one for normal and the other for the parallel) obtained through the k-eff-1D model, with the thermal conductivity obtained with the k-eff-mod model, as a function of the length of the heat source and the plate, plate thickness and copper layers to a heat source square.

The purpose of this article is to use the method k-eff-mod to get these correlations as a function of source area and the plate, the plate thickness and the copper layers, to a heat source rectangular and circular, and the other as a function of radius of the source, the length of the plate, the plate thickness and the copper layers, to circular heat source.

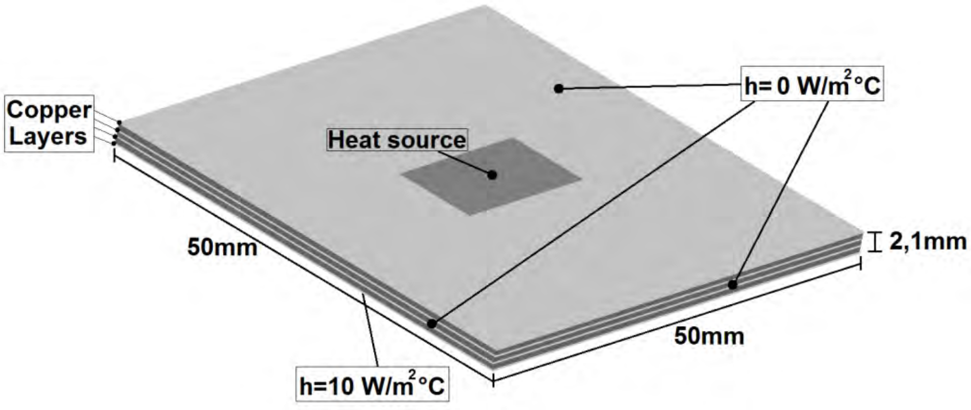

Figure 1 – Detailed model of the PCB with two copper inner layers and two outer layers of copper, solder side and component side

2. PROBLEM DESCRIPTION

To obtain correlations for the effective thermal conductivity of a PCB with a heat source, it is necessary to know the value of $k_{p,e}$, $k_{n,e}$, $k_{p,m}$ and $k_{n,m}$, that are the thermal conductivity parallel and normal for the k-eff-1D model and thermal conductivity parallel and normal for the k-eff-mod model respectively.

The equations 1 e 2, give the $k_{p,e}$ and $k_{n,e}$, respectively. To obtain $k_{p,m}$, and $k_{n,m}$, the numerical simulations were performed in two steps, first using the detailed model (PCB modeled with layers of copper and epoxy), and second, the simplified model (PCB was represented by a single object with effective thermal conductivity parallel and normal). The solutions were obtained for rectangular heat source and circular heat source.

The problem described below was modeled numerically and computer simulations were performed for the detailed model, which the plate was modeled in layers of glass-epoxy (k_g=0,25 W/m°C) and copper (k_c=390 W/m°C), see figure 1, and for the k-eff-mod model, the plate was modeled as a single object with a certain thermal conductivity to the plane parallel to the plate and another to the plane normal to the plate, see figure 2.

ISSN 2176-5480

Consider a 50 mm x 50 mm x 2,1 mm PCB with 35 µm thick internal copper layers and 17,5 µm thick external copper layers (lower and upper) as shown in figure 1. The internal copper layers are positioned uniformly in the PCB thickness. The top and sides of this PCB are insulated and the convection heat transfer coefficient and air temperature on the bottom side are 10W/m^2°C. The heat source centrally located on upper surface and it dissipates 2 W.

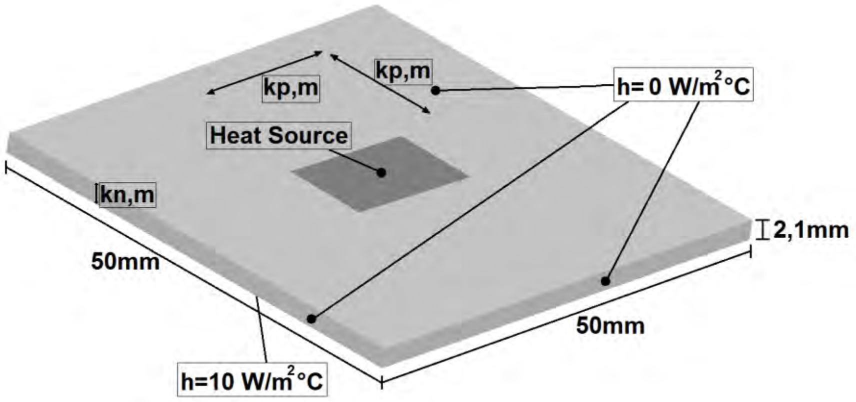

Figure 2 – Simplified model of the PCB with two copper inner layers and two outer layers of copper, solder side and component side

In the cases analyzed, the heat source does not have a constant geometry. It varies in size and shape and may be circular or rectangular, and can occupy at least 1% of the PCB area and maximum 51% for the rectangular geometry and 40% for circular geometry. Furthermore, the amount of copper inner layers can extend from 2 to 4. Tables 1 and 2 give a summary of all cases analyzed.

Table 1. Cases analyzed for a Rectangular Heat Source.

Number of Layers →	2	3	4
A_s/A_b (Heat Source Area/Board Area)	0,0101	0,0101	0,0101
	0,0240	0,0240	0,0240
	0,0577	0,0577	0,0577
	0,0960	0,0960	0,0960
	0,2160	0,2160	0,2160
	0,3110	0,3110	0,3110
	0,3840	0,3840	0,3840
	0,4860	0,4860	0,4860
	0,5189	0,5189	0,5189

For the situation described the k-eff-1D model has limitations. For given boundary conditions, the maximum heat source temperature, T_s, and the maximum temperature of the board opposite from the heat source, T_b, are functions of the PCB length, L_b, and thickness, t, number of copper layers, N_c, thickness of the ith copper layer, $t_{c,i}$, number of glass epoxy layers, N_g, thickness of the ith glass-epoxy layer, $t_{g,i}$, thermal conductivities of copper and glass-epoxy, k_c and k_g, and the length of the heat source , L_s.

$$T_s = f_1(L_b, t, N_c, t_{c,i}, N_g, t_{g,i}, k_c, k_g, L_s) \quad (3)$$

$$T_b = f_2(L_b, t, N_c, t_{c,i}, N_g, t_{g,i}, k_c, k_g, L_s) \quad (4)$$

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Table 2. Cases analyzed for a Circular Heat Source.

Number of Layers →	2	3	4
r_s/L_b (Heat Source radius/Board length)	0,0568	0,0568	0,0568
	0,0874	0,0874	0,0874
	0,1355	0,1355	0,1355
	0,1748	0,1748	0,1748
	0,2622	0,2622	0,2622
	0,3147	0,3147	0,3147
	0,3496	0,3496	0,3496
	0,3933	0,3933	0,3933
	0,0568	0,0568	0,0568

Now let's assume this PCB is modeled as a single object with different parallel and normal thermal conductivities. For the same boundary conditions, the maximum heat source and board temperatures are functions of the PCB length, L_b, and thickness, t, parallel and normal thermal conductivities of the PCB model, k_p and k_n, and the length of the heat source, L_s.

$$T_s = g_1(L_b, t, k_p, k_n, L_s) \tag{5}$$

$$T_b = g_2(L_b, t, k_p, k_n, L_s) \tag{6}$$

Equating equations 3 to 5 and equations 4 to 6 gives two implicit equations for the parallel and normal thermal conductivities. These equations show that the parallel and normal thermal conductivities of the PCB model have to be functions of the number, thickness and thermal conductivity of each copper and glass-epoxy layer as well as the heat source and board dimensions.

$$k_p = h_1(N_c, t_{c,i}, N_g, t_{g,i}, k_c, k_g, t, L_b, L_s) \tag{7}$$

$$k_n = h_2(N_c, t_{c,i}, N_g, t_{g,i}, k_c, k_g, t, L_b, L_s) \tag{8}$$

The k-eff-1D model neglects the dependence of k_p, and k_n on the heat source

3. RESULTS

Numerical solutions of the three dimensional heat conduction equations for a PCB and a heat source were used to establish correlations for equations 7 and 8. Two different representations of a PCB were simulated by ANSYS software Computational Fluid Dynamics (CFD). The first consisted of a PCB square of side 50 mm, modeled with details of copper and epoxy layers. A heat source in a rectangular shape (6.5 mm x 3.9 mm to 46.5 mm x 27.9 mm) was centered at the top of this PCB. The second representation is similar to the first, except that the PCB was represented by a single object with effective thermal conductivity parallel and normal. It was assumed that the top side of the PCB (the component side) was insulated and a heat transfer coefficient of 10 W/m^2°C were assigned to the bottom side of the PCB. This analysis was repeated for circular heat source (radius 2.8 mm to 20 mm).

The thermal conductivity parallel and normal were obtained by the method suggested by Shabani described in the introduction, however it were iteratively corrected such that the maximum heat source temperature (T_s) and the maximum PCB temperature (T_b) opposite the heat source were predicted at the second decimal values provided by the detailed simulation, in other words, to the temperature values obtained in the simulations, the iterative process ending when the temperature difference between the detailed model T_s and the k-eff-mod model T_s and the detailed model T_b and the k-eff-mod model T_b was less than 0.01%. This error of 0.01% was set because of the difficulty of obtaining a curve between $k_{p,m}/k_{p,e}$ x A_s/A_b . This means that to adjust the error with a thermal conductivity greater than or equal to 1%, the $k_{p,m}$ values vary widely, so this makes it difficult to obtain a graph of a trend line representing all points.

The convergence criteria were used for all the numerical solutions were reduction of the residual of the temperature equation below 10^{-12}.

The grid sensitivity of the numerical solutions was investigated. It was observed that for the mesh 50 x 50 x 60 elements of the models shown in figures 1 and 2, the change of T_s and T_b was in the order of 10^{-2} or 0.01% error, that the error was defined as mentioned above. For a mesh of 20 x 20 x 38 elements, the error obtained was about 1%, it does not satisfy the set. Therefore, the grid used for all the simulations was 50 x 50 x 60, generating a total of 150000 elements.

ISSN 2176-5480

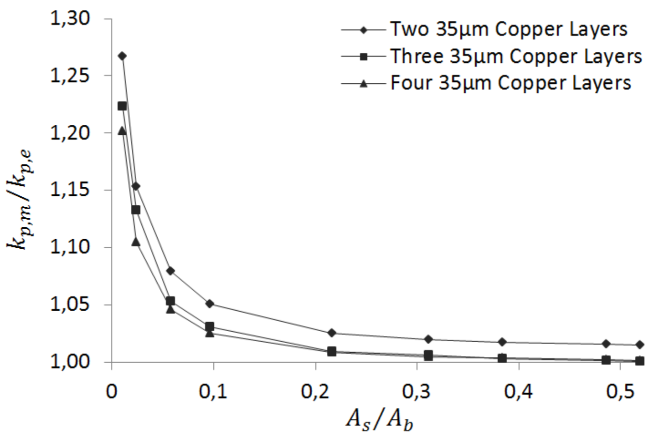

Figure 3 – Thermal conductivity parallel of the PCB with a rectangular heat source in function of the ratio between heat source area and plate area

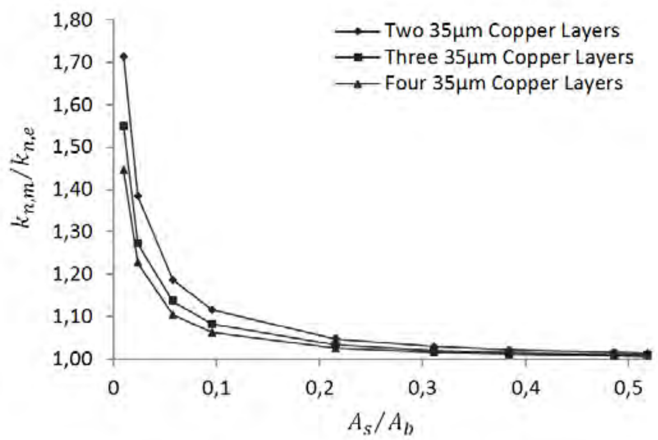

Figure 4 – Thermal conductivity normal of the PCB with a rectangular heat source in function of the ratio between heat source area and plate area

The numerical procedure above was repeated for different source sizes and source shapes to find the thermal conductivities parallel and normal for the k-eff-mod model, in function of the geometric characteristics of the plate and the heat source. The figures 3 and 4 show the ratio of thermal conductivities parallel and normal, between the k-eff-mod model and k-eff-1D model , $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ respectively, to a PCB with 2.1 mm thickness, in function of the ratio between the area of the heat source and the plate. It is noticed that $k_{p,m}$ is always greater than or equal to $k_{p,e}$. The ratio approaches the value 1 when the size of the heat source approaches the size of the PCB and/or when the number of inner copper layers increases.

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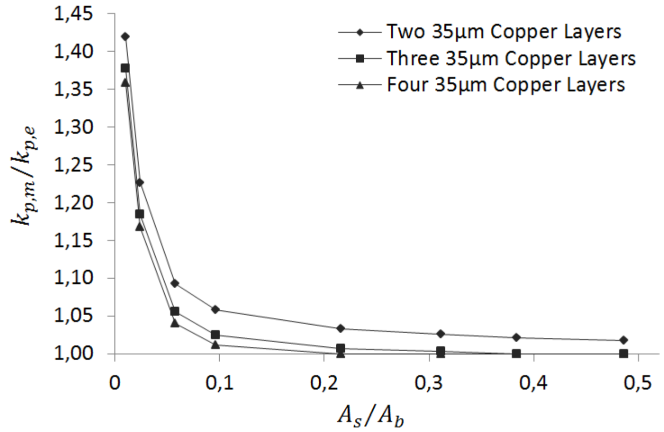

Figure 5 – Thermal conductivity parallel of the PCB with a circular heat source in function of the ratio between heat source area and plate area

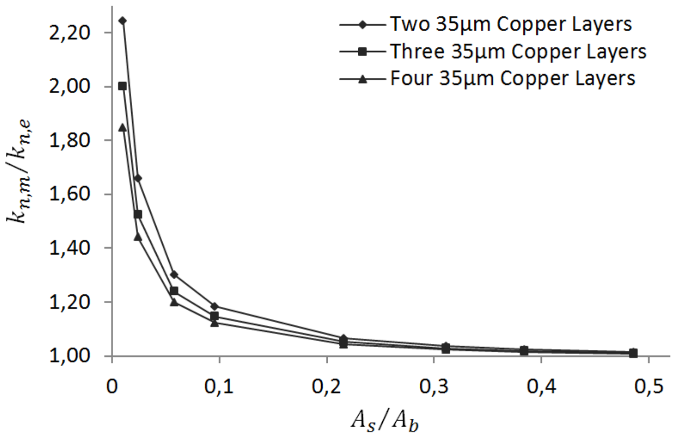

Figure 6 – Thermal conductivity normal of the PCB with a circular heat source in function of the ratio between heat source area and plate area

The figures 5 and 6 show the same procedures for the PCB with a circular heat source, and figures 7 and 8 show the results from the same scenario, but in function of the ratio between the radius of the heat source and the side of the square plate.

For the rectangular heat source, the analysis was performed only in function of the area, because as it is a rectangle the heat source has two distinct sides lengths, different from the circle and the square, which enables the analysis depending on the area, radius or side.

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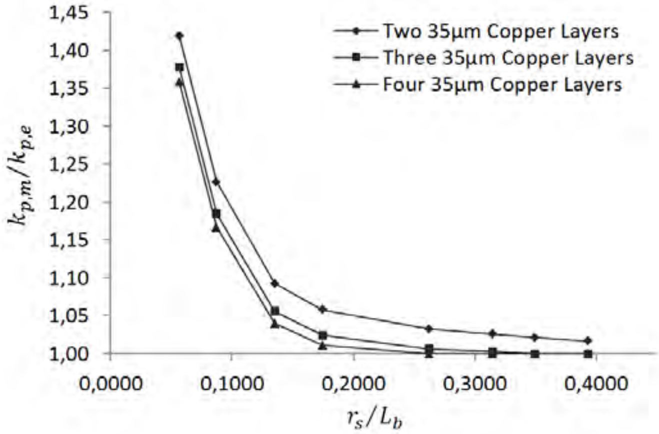

Figure 7 – Thermal conductivity parallel of the PCB with a circular heat source in function of the ratio between heat source radius and plate side

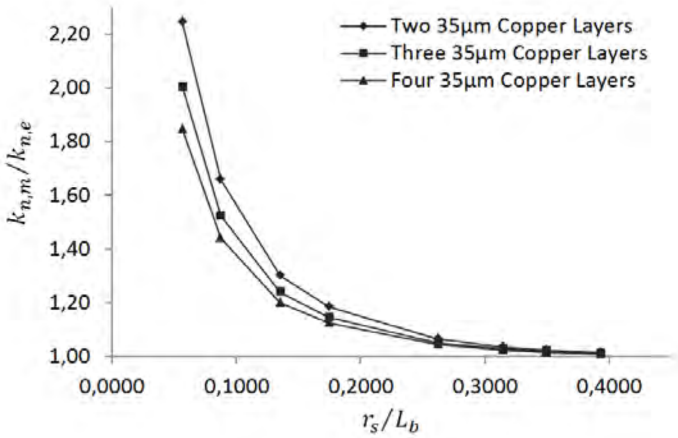

Figure 8 – Thermal conductivity normal of the PCB with a circular heat source in function of the ratio between heat source radius and plate side

The value of $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ that were plotted in figures 3, 4, 5 and 6 were also plotted as a function of the "scaled source area" which is defined as $[(A_s/A_b)(t_c/t)]^{0,5}$, where A_s is the area of heat source, A_b is the area of the PCB, t_c is the total thickness of all the layers of copper, and t is the thickness of the PCB. The value of the $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ that were plotted in figures 7 e 8 were also plotted as a function of the "scaled source length" which is defined as $(r_s/L_b)(t_c/t)^{0,5}$, where r_s is the radius of heat source, L_b is the side of the PCB. In such cases, the curves obtained in each case collapse into a single curve independent of the number of inner layers of copper.

The figures 9 and 10 show $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ in function of the scaled source area for the rectangular heat source.

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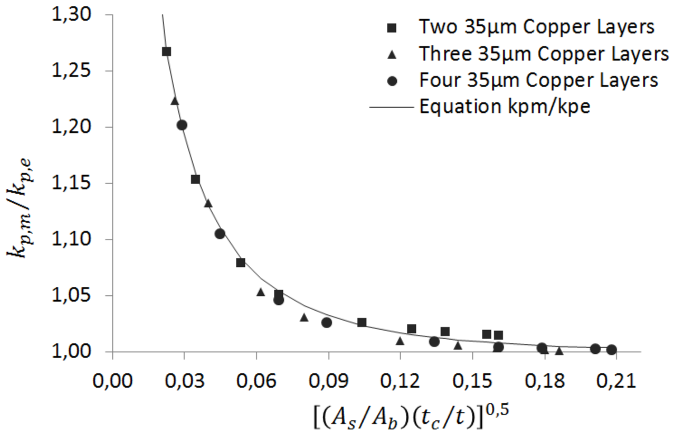

Figure 9 – Variation of the thermal conductivity parallel of the PCB with rectangular heat source in function of $[(A_s/A_b)(t_c/t)]^{0,5}$

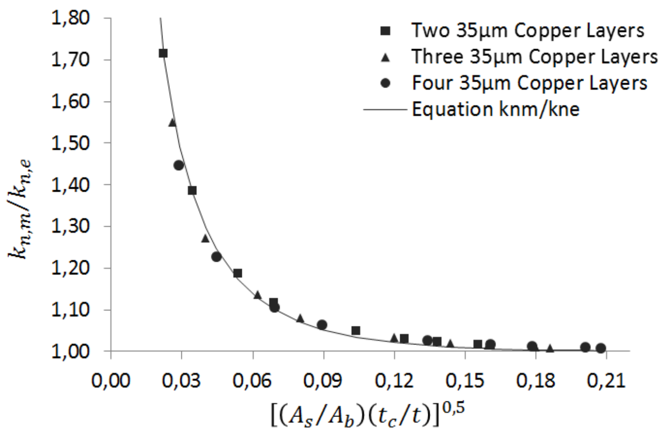

Figure 10 – Variation of the thermal conductivity normal of the PCB with rectangular heat source in function of $[(A_s/A_b)(t_c/t)]^{0,5}$

The figures 11 and 12 show $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ in function of the scaled source area for the circular heat source.

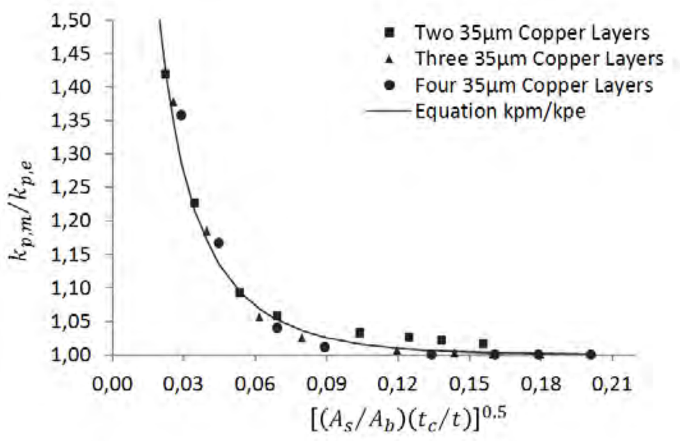

Figure 11 – Variation of the thermal conductivity parallel of the PCB with circular heat source in function of $[(A_s/A_b)(t_c/t)]^{0,5}$

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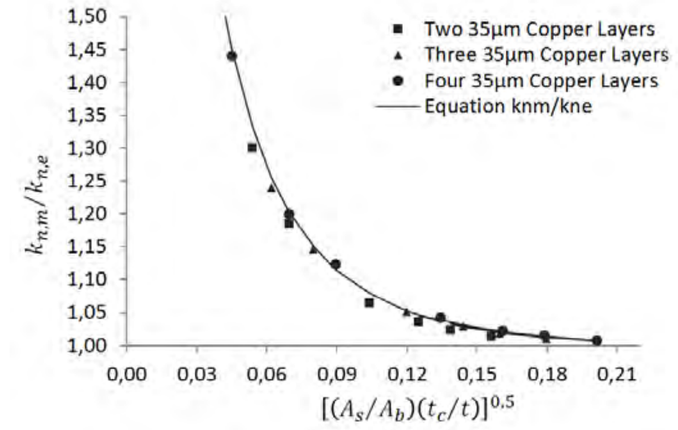

Figura 12 – Variation of the thermal conductivity normal of the PCB with circular heat source in function of $[(A_s/A_b)(t_c/t)]^{0,5}$

Finally, the figure 13 and 14 show $k_{p,m}/k_{p,e}$ and $k_{n,m}/k_{n,e}$ in function of the scaled source length for the circular heat source.

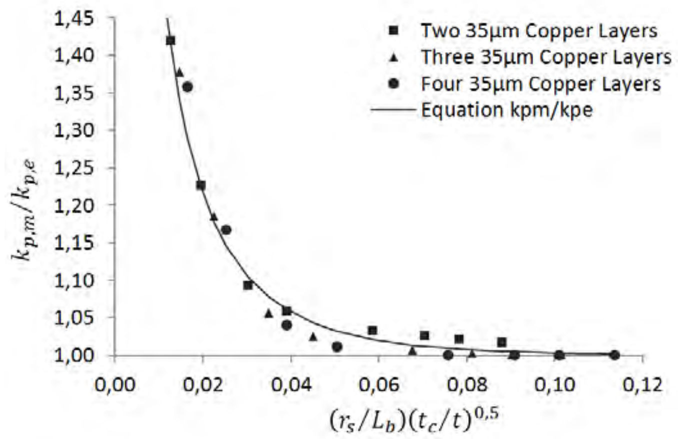

Figura 13 – Variation of the thermal conductivity parallel of the PCB with circular heat source in function of $(r_s/L_b)(\mathrm{tc}/t)^{0,5}$

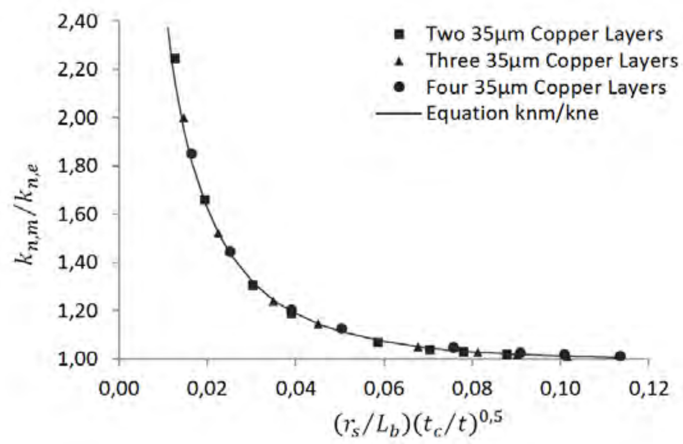

Figura 14 – Variation of the thermal conductivity normal of the PCB with circular heat source in function of $(r_s/L_b)(\mathrm{tc}/t)^{0,5}$

Appropriate correlations for these curves, which is the goal of this work, are given by equations 9 and 10 for the cases with the heat source rectangular in function of scaled source area, by equations 11 and 12, for the cases with the source heat circular in function of scaled source area, and the equations 13 and 14 for the cases with the circular heat source in function of scaled source length.

$$\frac{k_{p,m}}{k_{p,e}} = \left[1 - exp\left(-14\left(\left(\left(\frac{A_s}{A_b}\right)\left(\frac{t_c}{t}\right)\right)^{0,5}\right)^{0,58}\right)\right]^{-1} \tag{9}$$

$$\frac{k_{n,m}}{k_{n,e}} = \left[1 - exp\left(-25\left(\left(\left(\frac{A_s}{A_b}\right)\left(\frac{t_c}{t}\right)\right)^{0,5}\right)^{0,88}\right)\right]^{-1} \tag{10}$$

The equations 9 and 10 are the correlations for the rectangular heat source in function of the scaled source area.

$$\frac{k_{p,m}}{k_{p,e}} = \left[1 - exp\left(-25{,}5\left(\left(\left(\frac{A_s}{A_b}\right)\left(\frac{t_c}{t}\right)\right)^{0,5}\right)^{0,8}\right)\right]^{-1} \tag{11}$$

$$\frac{k_{n,m}}{k_{n,e}} = \left[1 - exp\left(-23\left(\left(\left(\frac{A_s}{A_b}\right)\left(\frac{t_c}{t}\right)\right)^{0,5}\right)^{0,96}\right)\right]^{-1} \tag{12}$$

The equations 11 and 12 are the correlations for the circular heat source in function of the scaled source area.

$$\frac{k_{p,m}}{k_{p,e}} = \left[1 - exp\left(-32{,}5\left(\left(\frac{r_s}{L_b}\right)\left(\frac{t_c}{t}\right)^{0,5}\right)^{0,75}\right)\right]^{-1} \tag{13}$$

$$\frac{k_{n,m}}{k_{n,e}} = \left[1 - exp\left(-34{,}3\left(\left(\frac{r_s}{L_b}\right)\left(\frac{t_c}{t}\right)^{0,5}\right)^{0,93}\right)\right]^{-1} \tag{14}$$

The equations 13 and 14 are the correlations for the circular heat source in function of the scaled source length.

4. CONCLUSION

The correlations presented here, equations 9 to 14 were obtained for a PCI square with 2.1 mm in thickness, two, three or four copper layers, evenly spaced, a layer of copper on the lower side and a layer of cooper on the upper side, uniform heat flow rectangular or circular centrally located on the PCB, and with the boundary conditions shown in figures 1 and 2. Therefore, the validity of these correlations for other conditions should be investigated.

For figures 9 to 14, it is clear that the collapse of the curves that treat thermal conductivity normal was more intense than the thermal conductivity parallel. This is due to greater sensitivity of T_s and T_b towards the normal thermal conductivity. The hypothesis is that the iterative process for obtaining $k_{p,m}$, if there are more points, as T_{s1}, T_{s2}, T_{s3}, ..., T_{sn} and T_{b1}, T_{b2}, T_{b3}, ..., T_{bn}, to compare the temperature between the detailed model and the k-eff-mod model, this problem would be eliminated.

For the circular heat source, was obtained two curves for the thermal conductivity parallel and two curves for the thermal conductivity normal. This is because the analysis was done in function of the area and the radius of the heat source. The relative error between them is about 5% and decreases with increasing heat source.

This article analyzed the effective thermal conductivity of a PCB with a single component of various sizes. For a PCB model with two or more heat source and other heat source formats, the use of these correlations must be made in order to determine the effective thermal conductivity for regions on the plate, but more research is needed.

ISSN 2176-5480

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