Artículo de investigación

Modeling and thermal analysis of heat sink layers of multilayer board

Моделирование и тепловой анализ теплоотводящих слоев многослойной платы

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Abstract

Issues of heat dissipation in multilayer printed circuit boards (PCB) are very important due to the increasing density of installation of electronic components. There are many approaches to solving the problem of reducing the temperature of electronic components from conductive and convective heat removal in vacuum and normal operating conditions prior to the use of fans and cooling radiators. In multilayer printed circuit boards, the most efficient is the removal of heat using heat-removing layers made of materials with a high degree of heat transfer: copper, aluminium, magnesium, etc., and of sufficient thickness for efficient heat dissipation. At the same time, as experience shows, an unjustified increase in the thickness of the heat-removing layers in multilayer printed circuit boards leads to a deterioration in the weight characteristics of multilayer boards with an inefficient heat sink. Therefore, the study of the effective thickness of the heat-removing layers and the materials used in this process is an important and urgent problem. Mathematical modelling of the module of an aircraft instrument containing a multilayer printed circuit board with heat-removing layers of various materials has been carried out. The convergence of the calculation results is checked by reducing the mesh of the finite element mesh. Heat removal was taken into account at different thicknesses of the heat-removing layer. The dependence of the heat sink on the thickness of the heat sink layer of the multilayer printed circuit board was revealed. This dependence was nonlinear in nature: with an increase in the thickness of the heat sink layer, the relative value of the heat sink decreased. As a result, the optimum thickness of the heat sink layer was

Аннотация

Проблемы рассеивания тепла в многослойных печатных платах имеют большое значение в связи с увеличением плотности монтажа электронных компонентов. Существует много подходов к решению проблемы снижения температуры электронных компонентов от кондуктивного и конвективного отвода тепла в вакууме и нормальных условиях эксплуатации до использования вентиляторов и радиаторов охлаждения. В многослойных печатных платах наиболее эффективным является отвод тепла с использованием теплоотводящих слоев, изготовленных из материалов с высокой степенью теплопередачи: меди, алюминия, магния и т. д. и достаточной толщины для эффективного отвода тепла. В то же время, как показывает опыт, необоснованное увеличение толщины теплоотводящих слоев в многослойных печатных платах приводит к ухудшению весовых характеристик многослойных плат с неэффективным теплоотводом. Поэтому изучение эффективной толщины теплоотводящих слоев и материалов, используемых в этом процессе, является важной и актуальной проблемой. Проведено математическое моделирование модуля авиационного прибора, содержащего многослойную печатную плату с теплоотводящими слоями из различных материалов. Сходимость результатов расчета проверяется путем уменьшения ячейки сетки конечных элементов. Отвод тепла учитывался при разных толщинах теплоотводящего слоя. Была выявлена зависимость теплоотвода от толщины теплоотводящего слоя многослойной

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obtained, at which an increase in thickness slightly affected the heat removal.

Keywords: Conduction, convection, finite element method, layers heat removal, PCB layers.

печатной платы. Эта зависимость носила нелинейный характер: с увеличением толщины теплоотводящего слоя относительная величина теплоотвода уменьшалась. В результате была получена оптимальная толщина теплоотводящего слоя, при которой увеличение толщины незначительно повлияло на отвод тепла.

Ключевые слово: конвекция, метод конечных элементов, проводимость, слои печатных плат, теплоотвод слоев.

Introduction

The issues of heat removal in electronic devices are important and this problem has received considerable attention in the literature (Khairnasov, 2013; Vintrou, Laraqi, Bairi, 2012; Costa, Vlassov, 2013; Funk, Mengüç, Tagavi, Cremers, 1992; Muzychka, Yovanovich, Culham, 2006; Rinaldi, 2006; Muzychka, Bagnall, Wang, 2013; Monier-Vinard, Laraqi, Dia, Nguyen, Bissuel, 2013; Shabany, 2002; Schacht, Wunderle, May, Michel, Reichl, 2008; Dede, Nomura, Lee, 2015). Various methods are used to reduce the temperature: installation of electronic components having a temperature close to or above the permissible ones on radiators. Blowing components with fans, installing electronic modules on thermostabilizing platforms that maintain a constant temperature. Cooling using heat sink tires, use of channels to remove heat in the body of electronic modules by air or liquid purging. All these methods of heat removal lead to an increase in the mass-dimensional characteristics of products and do not always lead to a solution to the problem.

One of the most effective methods of heat dissipation from electronic components is the location in the circuit board of heat-removing layers made of copper or aluminium layers. At the same time, taking into account such heat-releasing layers to lower the temperature of electronic components requires the improvement of calculation methods and experimental studies. The solution to this problem, taking into account all electronic components that make up the device, workloads, environmental conditions, physical and mechanical characteristics of materials, is possible only using numerical methods. A numerical method such as the finite element method allows you to get the temperature any point in the product. The solution of the problem is reduced to solving a system of an inhomogeneous linear system of equations. Importance when modelling a multilayer printed circuit board is to take into account the thickness of the layers of up to 18 microns, as well as provide for the transfer of heat from the heat-conducting layers to the body of the product. For this, the ends of the printed circuit board are bordered by heat-removing materials, in most cases, copper connected to the product body.

The present work is devoted to the issues of modelling and thermal analysis of electronic devices having a multilayer printed circuit board with heat-removing layers. Multilayer printed circuit boards are used in many aircraft instruments and heat removal issues are of current importance.

Electronic devices used in aviation must have enhanced reliability characteristics, due to the large consequences of their failure during operation. One of the factors ensuring the reliability of electronic devices used in aeronautical engineering is reliable mechanical and thermal calculation (Levashkin, Ogin, Vasilyev, 2019; Vantsov, Vasilyev, Medvedev, Khomutskaya, 2019). Exceeding the permissible thermal operating conditions of electronic components leads to the failure of these elements and ultimately to the failure of the electronic device with unpredictable consequences during the flight. One of the factors affecting the heat sink in multilayer printed circuit boards, which are of great use in aircraft devices, is the thickness and material characteristics of the heat sink layers. A significant number of works have been devoted to heat removal issues (Khairnasov, 2013; Vintrou et al., 2012; Costa, et al., 2013; Funk et al., 1992; Muzychka et al., 2006; Rinaldi, 2006; Muzychka et al., 2013; Monier-Vinard et al., 2013; Shabany, 2002; Schacht et al., 2008; Dede et al., 2015).

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At the same time, the issue of optimal thickness, thermal characteristics, location and structure of heat-removing layers in multilayer printed circuit boards has not yet been resolved. An unjustified increase in the thickness of the heat-removing layers affects the mass characteristics of aviation devices, which are of great importance in aviation.

Heat dissipation in multilayer printed circuit boards is essential for the performance of printed circuit boards. Exceeding the permissible temperature of the components of the printed circuit board leads to the exhaustion of the operability of the elements and, ultimately, to the failure of the electronic device (Costa, Vlassov,2013; Dede, Nomura, Lee, 2015).

Currently, the consideration of this problem has not got enough attention, because multilayer printed circuit boards are widespread. This problem was considered in the articles (Khairnasov, 2013), where the thermal regimes of radioelectronic equipment, intended for operation in the unpressurized compartments of full-size or small spacecraft, are investigated. The problem is solved by the finite element method. The effect of the thickness of the intermediate copper layers of the board on the thermal conditions of the electronic equipment is also being studied. Mathematical modelling of the thermal conditions of an electronic unit operating in a state of zero gravity has shown that the introduction of additional layers of copper into multilayer printed circuit boards provides the necessary temperatures of thermally stressed radio electronic elements. At the same time, many parameters affecting the heat sink in multilayer printed circuit boards require their detailed consideration (Muzychka, Yovanovich, Culham, 2006; Muzychka, Bagnall, Wang; 2013).

Multilayer printed circuit boards are a structure consisting of metal layers, designed to remove heat from electronic components and switching (conductive pattern) between components and dielectric layers, designed to perform carrier functions for electronic components.

Heat transfer layers in multilayer printed circuit boards are important for the functioning of an electronic device due to the increasing density of mounting electronic components and, as a consequence, the increased power output of an electronic device. The optimal parameters of heat removing layers require determination: an unjustified increase in the thickness of these layers leads to an increase in the mass characteristics of the device with a slight effect of heat removal (Funk, Mengüç, Tagavi, Cremers, 1992; Monier-Vinard, Laraqi, Dia, Nguyen, Bissuel, 2013). The mass characteristics of electronic devices are defining parameters when used in the aviation industry. Insufficient attention has been paid to the problem of the optimal thickness of the heat-removing layers of printed circuit boards, given that heat removal is indirectly related to the thickness of the heat-removing layer and the arrangement of these layers in the structure of a multilayer printed circuit board. In this paper, we consider the influence of the location, thickness, and physicomechanical characteristics of heat-removing layers of a multilayer printed circuit board on the heat removal from electronic components and the determination of the optimal parameters of such layers.

Theoretical basis

The problem is solved by the finite element method. The accuracy of the obtained calculations was checked by thickening the grid of finite elements and, if the results differ by no more than 2-3%, for the previous and subsequent approximation this is a sufficient condition for a solution problem.

Insufficient attention has been paid to the problem of the optimal thickness of the heat-removing layers of printed circuit boards, given that heat removal is indirectly related to the thickness of the heat-removing layer and the arrangement of these layers in the structure of a multilayer printed circuit board (Rinaldi, 2006; Vantsov, Vasilyev, Medvedev, Khomutskaya, 2019). A four-layer and six-layer printed circuit board with electronic components located on it is considered. Heat-removing layers are connected with a copper bordering of the perimeter of a printed circuit board connected to the electronic device housing. Convective and conductive heat removal was considered (Vintrou, Laraqi, Baïri, 2012; Levashkin, Ogin, Vasilyev, 2019). The electronic device is installed on a thermal stabilization platform with a temperature of plus 40 ° C. The dimensions of the board were 150 by 175 mm with a thickness of 1.6 mm. The ambient temperature is ± 40 ° C. In the calculations, plus 40 ° C was taken as the worst-case load module. Intermediate heat-removing layers with filling of 30, 50, 70, 90 and 100%. The board is located in a sealed enclosure at normal atmospheric pressure. An electronic component generates a power of 0.4 watts. Heat transfer layers were made of aluminum (Al) and copper (Cu) with a density of 2700 and 8900 kg / m^3 and thermal conductivity of 200 and 380 W/mK, respectively. The dielectric FR-4 have a density of 1250 kg/m^3 and thermal conductivity of 0,35 W/m K.

The modelling process consisted in calculating the maximum temperature of the components for each of the variants of the basic structure of the module, which differ from each other in the thickness of the metallization layers (Shabany, 2002; Schacht, Wunderle, May, Michel, Reichl, 2008). With the increase in the latter, based on the condition of maintaining the total package thickness of 1.6 mm, thickness of the dielectric decreases. This reduction is taken into account by uniformly distributing the thickness deficit across all layers of the dielectric. An example of such a distribution for one of the calculated options is given in the Table 1.

Table 1. Parameters of four-layer PCB

Layer material	Layer thickness (µm)									
Copper	18	35	70	105	140	175	210	245	280	315
FR-4	509	487	463	440	417	393	370	207	160	113
Copper / Aluminum	18	35	70	105	140	175	210	245	280	315
FR-4	509	487	463	440	417	393	370	207	160	113
Copper / Aluminum	18	35	070	105	140	175	210	245	280	315
FR-4	509	487	463	440	417	393	370	207	160	113
Copper	18	35	70	105	140	175	210	245	280	315

Methodology

To solve the problems of thermal conductivity, various methods are used: analytical, numerical, graphical, etc. In this paper, we used the most common numerical method: the finite element method, which has proven itself in solving various problems of mechanics and the thermal of conductivity.

The construction of module (Figure 1) was modelled by a set of 20-node quadratic hexahedral finite elements of 3D conductivity.

Using the variation principle of Hamilton-Ostrogradsky allows us to reduce the problem of thermal conductivity of a multilayer printed circuit board with heat-removing layers and elements located on the board to a system of linear inhomogeneous equations.

The equation of linear static thermal conductivity is determined from the equation:

$$Q = C \times T$$

where C is the matrix of conductivities, depending on the material (W/ºC); T is the unknown temperature in the nodes to be determined (ºC); Q is the heat source, defined as the load (Watt).

As an external load applied to the boards, intensity of the distributed heat per unit area applied to the edges of the structural elements (W/m^2) and the intensity of the distributed heat per unit volume (W/m^3), as well as the external temperature plus 40 ° C applied to the installation surface.

As a result of the study, the temperature in the nodes of the final elements was determined. The total number of finite elements of the partition was 53034. The accuracy of the obtained calculations was checked by thickening the grid of finite elements. The calculation error when splitting at 61220 and the adopted splitting scheme was ~ 2.5%. Such an error makes it possible to obtain reliable results, bearing in mind that the calculation programs used were repeatedly checked for the accuracy of the solutions obtained.

Results

As a result of the study, the dependences of the thickness of the heat-releasing layers and the characteristics of the materials from which they are made to the heat sink in multilayer printed circuit boards are obtained.

Figure 1 shows an example of visualization of simulated results.

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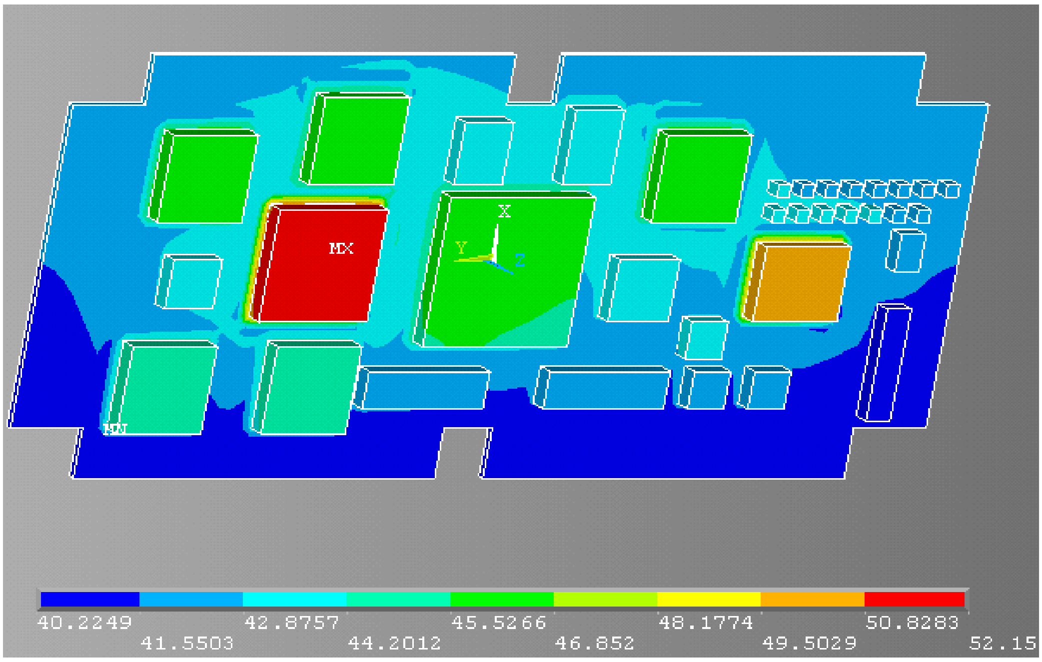

Figure 1. Example of visualization of simulated results. Temperature distribution in a printed circuit board from 40 to plus 52.1°C

The tables below show the results of the thermal calculation of the on-board computer complex module; dependences of the maximum EPR temperature on the thickness of the multilayer board and the material from which the intermediate layers are made are showed.

Table 2. Variation of the maximum temperature of the components. The temperature values for heat-removing layers of aluminum and copper

Metallayers	Layer thickness (µm)									
1	18	35	70	105	140	175	210	245	280	315
2	18	35	70	105	140	175	210	245	280	315
3	18	35	70	105	140	175	210	245	280	315
4	18	35	70	105	140	175	210	245	280	315
T° temperature, °C, Al	109,3	80,3	63,4	57,2	53,9	51,8	50,4	49,3	48,5	47,8
T° temperature,°C, Cu	78,3	62,8	53,6	50,1	48,3	47,1	46,3	45,7	45,2	44,9

The analysis of the results obtained based on the calculation results showed that:

- Maximum temperature of the components is in nonlinear dependence on the thickness of the heat-removing layers of the multilayer printed circuit board;
- Effective thickness of heat-removing layers for copper is 70-175 microns;
- Effective thickness of heat-removing layers for copper is 105-245 microns.

Under the effective thickness of the heat sink layer is meant the thickness at which the temperature change with increasing thickness by 35 microns does not change more than 1 to 3 ° C.

The following tables show the calculation results for four-layer (Table 2 and 3) and six-layer (Table 4) printed circuit boards for various combinations of the parameters of the layers.

Table 3. Change in the maximum temperature of the components depending on the thickness of the heat sink layers and the type of material from which they are made. In the structure there are two mounting layers of constant thickness and two heat dissipating, with increasing thickness

Metallayers	Layer thickness (μm)									
1	35	35	35	35	35	35	35	35	35	35
2	18	35	70	105	140	175	210	245	280	315
3	18	35	70	105	140	175	210	245	280	315
4	35	35	35	35	35	35	35	35	35	35
T_o temperature, ºC, Al	93,1	80,3	67,5	61,2	57,4	54,9	53,0	51,6	50,5	49,7
$T_o$temperature, ºC, Cu	70,6	62,8	55,4	51,9	49,8	48,4	47,4	46,7	46,1	45,6

Table 4. Change in the maximum temperature of the components depending on the thickness of the heat sink layers and the type of material from which they are made. In the structure there are two assembly layers of constant thickness and four heat-removing layers with increasing thickness

Metallayers	Layer thickness (μm)									
1	35	35	35	35	35	35	35	35	35	35
2	18	35	35	53	70	88	105	123	140	158
3	18	18	35	53	70	88	105	123	140	158
4	18	35	35	53	70	88	105	123	140	158
5	18	18	35	53	70	88	105	123	140	158
6	35	35	35	35	35	35	35	35	35	35
T_o temperature, ºC, Al	79,4	74,1	69,9	64,7	61,7	59,6	58,1	56,9	56,0	55,2
$T_o$temperature, ºC, Cu	62,2	59,7	57,5	55,0	53,5	52,5	51,8	51,2	50,8	50,4

When designing, the intermediate heat sink (conductive) layers of multilayer printed circuit boards have a topology of different occupancy. Therefore, when making thermal calculations, it is necessary to take into account the occupancy of the heat-removing layers. It is not possible to take into account the whole diversity of topology; therefore, the calculations consider the uniform distribution of the heat-removing layer (that is, the uniform “smearing” of the layer over the entire surface).

Conclusion

Mathematical modeling of module of an aircraft instrument containing a multilayer printed circuit board with heat-removing layers of various materials has been carried out. The convergence of the calculation results is verified by reducing the cell of the finite element mesh. The optimal value of the finite element expansion is revealed, at which the results obtained for different numbers of module partitions differ by no more than 2-3%. Heat removal was taken into account at different thicknesses of the heat-removing layer. In this case, the dependence of the value of the heat sink on the thickness of the heat sink layer of the multilayer printed circuit board was revealed. This dependence was nonlinear in nature: with an increase in the thickness of the heat sink layer, the relative value of the heat sink decreased. As a result, the thickness of the heat sink layer was revealed at which an increase in the thickness slightly affected the heat removal. At the same time, the mass characteristics of the layer unjustifiably increased. The characteristics of materials that affect heat dissipation are also of great importance when considering the problems of heat dissipation in multilayer printed circuit boards. Therefore, various materials for heat sink layers were considered. Basically, in multilayer printed circuit boards, layers of copper alloys are used to remove heat. Aluminum layers are also used, which have high thermal conductivity.

Mathematical modeling of thermal modes of a multi-layer printed circuit board of a module operating in normal atmospheric conditions in an unpressurized case installed on a heat stabilization platform with a temperature of 40 ° C, performed by the finite element method, showed that:

- Use of internal heat-removing layers in the composition of multilayer printed circuit boards ensures the required temperatures of electronic components.
- Thickness of the layers significantly affects the heat sink, which is in a non-linear dependence on the characteristics of the layers;
- The most effective thickness of the heat-removing layer from copper is in the range of 70-175 microns;
- Further increase in the thickness of the copper layer does not lead to a significant change in the thermal regime, while the cost and weight characteristics of the board increase, which is irrational for devices used in aeronautical engineering, where the weight characteristics are priority;
- For aluminum, the effective thickness is 105-245 microns.

The results can be used in the design and manufacture of multilayer printed circuit boards, modeling and manufacturing of electronic devices for aircraft.

References

Costa R.L., Vlassov V., (2013). Evaluation of Inherent Uncertainties of the homogeneous Effective thermal Conductivity Approach in Modeling of Printed Circuit boards for Space Applications. Journal of Electronics Cooling and Thermal Control. 3, 35-41.

Dede E., Nomura T., Lee J. (2015). Design of anithotrupic thermal conductivity in multilayer printed circuit boards. IEEE Transactions on Components, Packaging, and Manufacturing Technology Institute of Electrical and Electronics Engineers. 5(12), 1763-1774.

Funk J.N., Mengüç M.P., Tagavi K., Cremers C.J., (1992). Semi-Analytical Method to Predict Printed Circuit Board Package Temperature. IEEE Transaction on components, hybrids and manufacturing technology. 15(5), 675-684.

Khairnasov K.Z. (2013). Modeling and thermal analysis of electronic devices of spacecraft. Bulletin of Moscow Aviation Institute. 3, 56-61.

Levashkin D., Ogin P., Vasilyev F.V. (2019). Efficiency of hybrid cyclic processing with the use of additive technologies on CNC machines for the manufacture of composite aviation parts due to the reduction of processing errors. International Russian Conference on Materials Science and Metallurgical Technology, Vladivostok, Russia. 946, 959-965.

Monier-Vinard E., Laraqi N., Dia C.T., Nguyen M.N., Bissuel V. (2013). Analytical Thermal Modeling of Multi-Layered Active Embedded Chips into High Density Electronic Board. Thermal Science. 17(3), 695-706.

Muzychka Y.S., Bagnall K. R., Wang E. N. (2013). Thermal Spreading Resistance and Heat Source Temperature in Compound Orthotropic Systems With Interfacial Resistance. IEEE Transactions on Components, Packaging and Manufacturing Technology. 3(11), 1826-1841.

Muzychka Y.S., Yovanovich M.M., Culham J.R., (2006). Influence of Geometry and Edge Cooling on Thermal Spreading Resistance. Journal of Thermophysics and Heat Transfer, 20(2), 247-255.

Rinaldi N. (2006). Generalized Image Method with Application to the Thermal Modeling of Power Devices and Circuits, IEEE Transactions on Electron Devices, 49(4), 679-686.

Schacht R., Wunderle B., May D., Michel B., Reichl H. (2008). Modeling Guidelines and Non-Destructive Analysis for Thermal and Mechanical Behaviour of Via-Structures in Organic Boards. Thermal and Thermo-mechanical Phenomena in Electronic Systems Conference, 441-449.

Shabany Y. (2002). Component size and effective thermal conductivity of Printed Circuit Board. Inter Society Conference on Thermal Phenomena, 13.

Vantsov S., Vasilyev F., Medvedev A., Khomutskaya O. (2019). Epoxy-glass composite materials for substrate printed circuit boards gigabit electronics. Amazonia Investiga, 8(22), 434-442.

Vintrou S., Laraqi N., Baïri A., (2012). Calculation and analysis of thermal impedance of microelectronic structures from analytical models. Solid-State Electronics. 67, 45-52.