

Modelling thermal behavior of surface mounted components during reflow soldering

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Abstract

Nowadays reflow soldering is the most widespread technology used for electrical and mechanical attachment of surface mount devices (SMDs) to printed wiring boards (PWBs). In recent reflow ovens the required temperature to remelt the solder was typically achieved by forced convection. Nevertheless the thermal conduction is also important for the exact description of the soldering process because the heat spreads inside the components and within the PWB. Despite of the thermal profile optimization of the oven, inhomogeneous thermal distribution can form in the PWB and in the large-size SMD components. This effect could generate unexpected reflow soldering failures. With the aim of proper thermal modelling these failures can be eliminated.

Thermal investigation of components during reflow soldering is very special problem. This objective demands to apply special conditions in the thermal models, which highly differ from the common ones. Hence we have decided to develop a special thermal modelling tool. The model designing aspects which defined the way of development are presented in the paper. The mathematical description and formalism of the modelling tool are presented in the paper as well.

Keywords

thermal modelling · thermal nodes · reflow soldering

1 Introduction

Reflow soldering is a process to form electrical and mechanical connections between SMDs and PWBs. In state-of-the-art reflow ovens; merely forced convection heating is applied to heat the solder alloy above its melting point, thus two major issues are necessary to study: convection in the blown gas and the thermal conduction in solids (components, PWB) and in the liquid solder. The investigation of reflow soldering is inspired by the previous analysis of soldering failures, which are formed in the case of large-size devices. Inhomogeneous thermal distribution can emerge during reflow soldering around and within the large-size components due to the size and the high thermal capacities, and this inhomogeneity can lead to soldering failures.

Nowadays several excellent and usable 2D or 3D thermal simulation tools and models are available, but usually these are specialized to general thermal problems. However, the thermal investigation of components during reflow soldering is very special. Therefore the assumptions and the boundary conditions differ from the commons as well as the thermal system never reaches equilibrium state. Furthermore, our self-developed thermal modelling tool is well-applicable in the case of other special problems as the laser ablation [17].

The above mentioned reasons have led to develop a special thermal modelling tool. The core algorithm is based on the theory of thermal nodes. The applied mathematical description and formalism are presented further in details. Efficient mesh generator routine was required by the tool, which routine is also presented. The software has been developed by the aid of Matlab due to its ease of use. Further advantage of the Matlab software is its effective and powerful differential equation solver functions, so the simulations do not have large time consumption.

2 Possibilities of thermal modelling

At first glance thermal modelling means the solution of differential equation of thermal conduction. The real investigated issue defines the initial and the boundary conditions, which have to be taken into consideration during the solution of equations. An applied modelling tool is only suitable for the solution of the problem, if the preferred conditions are integrated.

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In recent wide range of modelling software and tools are available for users. In practice issue-specific tools for common issues exist. Such specificity has advantages, since those tools are able to solve the given issue precisely considering large range of conditions. In addition, they are user-friendly: users should not learn the mathematical background, but the handling of the graphical user interface only. Finally, the applied way of solution is very effective thus run time is short, because integrated algorithms are optimized for solving equations belonging to a specific problem. Certainly, the disadvantage of that solution is that tool is only applicable for handling problems it is actually specific for. In case of rarely occurring boundary condition or coupled physical phenomenon is included in the task to be solved, those tools can not be used. Among thermal modelling tools, there are wide varieties of specific software suitable for thermal modelling electronic components, circuits, parts and devices. Generally, software in the above fields is the most prevalent. The logical reason of the extent of prevalence is that designers are facing more difficult problems because of the gradual miniaturizing of electronic devices. Thermal modelling instruments are essential to design the latest component cases and cooling solutions. Consequently, large amount of modelling software such as Sunred [3], Therman [4], Flomerics [5], Celsius [6] are available on the market recently.

Another remarkable group of modelling software do not focus on common real issues, but function as general equation solver. They can be considered as a transition between self-developed modelling tools and issue-specific software. The aim of their development is to create a tool applicable for solving a wide range of physical problems. One of their advantages is that the user has full of freedom. Additionally, differential equations of the problem can be used directly. A large scale of initial and boundary conditions can also be defined. The interval to be analyzed can be defined and edited by a user-friendly graphical interface. Disadvantages are the more complicated traceability, generally the considerable demand of hardware and the long run time during simulation process. In case of several problems and task difficulties, those software could need powerful hardware. Moreover, there can be problems with special demands that those software can not solve. Such common software are Comsol Multiphysics [7], Matlab PDE toolbox [8], Ansys [9], Physica [10].

3 Theoretical background of the thermal node method

3.1 The differential equation of heat conduction [1]

Thermal modelling is based on the common differential equation of heat conduction. The following assumptions are made to create the equation:

- The examined range is an infinite volume dV
- There is a thermodynamic equilibrium in dV
- Faces of the cell is permeable for thermal interaction
- The difference of the energies entering into the cell and quitting out from the cell and the energy generated in the cell

(interior source) as a whole is used to change the enthalpy of the cell.

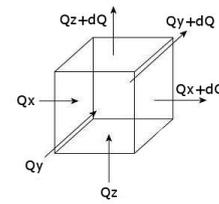


Fig. 1. Thermal flux components

The spatial inhomogeneity of the temperature is the reason for the transport of energy in the components of the PWB, which is quantitatively defined by the Fourier's law. The examined volume with the denotation of the heat flux components is illustrated by Fig. 1.

The difference of entering and quitting heat flux in direction x in the cube with $dx - dy - dz$ elemental edges:

$$Q_x(x) - Q_x(x + dx) = \frac{\partial}{\partial x} \cdot \left(-\lambda \cdot \frac{\partial T}{\partial x} dydz \right) dx \quad (1)$$

where T is the temperature and λ is the coefficient of thermal conductivity. The equations belonging to other directions are similar. Energy balance of volume dV : generated energy (entering and quitting heat flux) = change in enthalpy. The energy balance in mathematical form:

$$Q dx dy dz - \left[\frac{\partial}{\partial x} \cdot \left(-\lambda \cdot \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \cdot \left(-\lambda \cdot \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \cdot \left(-\lambda \cdot \frac{\partial T}{\partial z} \right) \right] dx dy dz = \rho \cdot c (dx dy dz) \cdot \frac{\partial T}{\partial t} \quad (2)$$

where Q is the heat flux generated by the interior heat source, ρ is the density and c is the specific heat. The simplified equation:

$$Q + \left[\frac{\partial}{\partial x} \cdot \left(\lambda \cdot \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \cdot \left(\lambda \cdot \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \cdot \left(\lambda \cdot \frac{\partial T}{\partial z} \right) \right] = \rho \cdot c \cdot \frac{\partial T}{\partial t} \quad (3)$$

If λ is independent from x , y and z , the equation can be simplified:

$$Q + \lambda \cdot \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] = \rho \cdot c \cdot \frac{\partial T}{\partial t} \quad (4)$$

3.2 Thermal node method [11], [15]

Let consider the one-dimensional form of the common differential equation of heat conduction:

$$\frac{\partial T}{\partial t} = a^2 \Delta T \quad (5)$$

where a is the coefficient of temperature conductivity, $a = \frac{\lambda}{\rho c}$. The principle of the thermal node method is that the nodes are

defined in the geometry, and the temperature of those nodes is examined. Nodes are considered as non-dimensional objects locating in the geometric centre of elements with finite volume. The size and geometric shape of the elements depend on the applied resolution and the type of the applied mesh. In the simplest case a Cartesian mesh is applied, where elements are cubic shaped, but other meshes can be used as well e.g. where elements are parallelepipedons. The thermal connections (thermal resistance) between the nodes are provided by the geometry of finite-volume elements and the thermal parameters of materials. Those parameters also determine the thermal capacitance assigned to each node. Thermal connections, capacitance, initial and boundary conditions define the change of node temperature. The illustration of thermal nodes can be seen in Fig. 2.

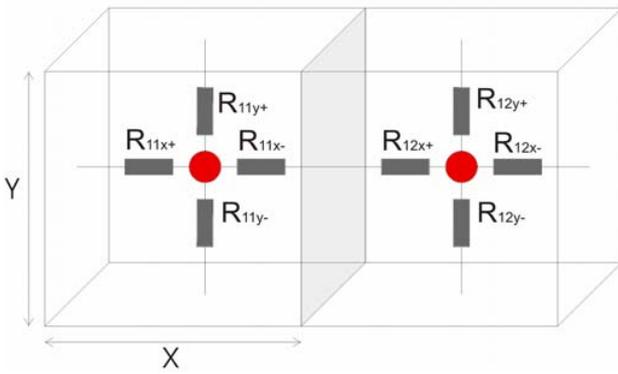


Fig. 2. Thermal nodes

The handling of these connections enables the modelling of heat distribution inside the body. The above principle is significantly different from e.g. the methods based on finite differences, so there are remarkable differences in the way of solution as well [2].

Thermal resistance between nodes is calculated by the thermal Ohm's law (following equations represents one-dimensional case):

$$R = \frac{x}{\lambda F} \quad (6)$$

where R is the thermal resistance, x is the distance between two nodes, λ is the coefficient of thermal conductivity and F is the surface, which the heat flux is flown through. If the thermal resistance is given, then the heat flux is flowing between two nodes:

$$Q = \frac{T_n - T_{n+1}}{R} \quad (7)$$

where T_n is the temperature of the n^{th} node.

In case of, when the values of thermal resistance and capacitance assigned to nodes are given, the temperature of a node in function of time can be calculated by the following equation:

$$T_n(t + dt) = T_n(t) + \frac{Q}{C_n} dt \quad (8)$$

where C_n is the thermal capacitance of the n^{th} node:

$$C = c \cdot \rho \cdot V \quad (9)$$

where V is the volume of the element.

Heat loss has to be considered of the nodes on the boundary of the range. Equations of those nodes are similar but in heat flux calculations beside (7) the Newton formula is additionally involved in Eq. (8):

$$Q = \alpha \cdot F \cdot (T_a - T_n) \quad (10)$$

where α is the heat transmission coefficient, T_a is the temperature of the gas or liquid.

4 Matlab-based thermal modelling tool

To summarize, the thermal node modelling tool is supposed to solve Eq. 8) considering the geometry, material parameters, initial and boundary conditions given by the user. The three-dimensional format of Eq. 8) is the following:

$$T_{x,y,z}(t + dt) = T_{x,y,z}(t) + \frac{Q_{x,y,z}}{C_{x,y,z}} dt \quad (11)$$

where

$$Q_{x,y,z} = \sum_{n:x=\pm 1,y=\pm 1,z=\pm 1} \frac{T_n(t) - T_{x,y,z}(t)}{R_{x,y,z}} \quad (12)$$

is the heat flux assigned to node $T_{x,y,z}(t)$. The definition takes into account the neighbouring nodes. The temperature of the neighbouring nodes are denoted by $T_n(t)$, in case they are included inside the volume $T_{x,y,z}(t)$.

The way of the solution can be divided into three major steps:

- 1 Definition of nodes and thermal connections between the nodes
- 2 Creation of system of equations to be solved
- 3 Solution of system of equations.

4.1 Definition of nodes and thermal connections between nodes

The definition of nodes and the calculation of the assigned geometric parameters are completed according to the geometric data given by the user. Cartesian mesh is applied, and at the beginning of the process its density is constant in each direction. This implies that each element could have maximum neighbours of six. The local compression or rarefaction of the mesh can take place later. The examined region can be rectangular shape. The mesh is determined by the software using the size of the region and the resolutions applied in different directions as input parameters. The elements (thermal nodes) of the mesh are denoted by numbers, as illustrated by Fig. 3. The resolution in this example is 2 in directions x and z , while 1 in direction y .

The calculation, the storage and handling of the place of nodes in the grid and the relations between neighbouring nodes are vital points. If one element has maximum neighbours of six only, the nodes can be sorted into a three-dimensional matrix in such way that their place in the matrix represents their

place in the mesh same and consequently the relations between neighbouring nodes can be handled easily. This method is only applicable if the density of the mesh cannot be changed. To handle the nodes and the relations between neighbouring nodes, a descriptive structure is created by the software, shown by expression (13).

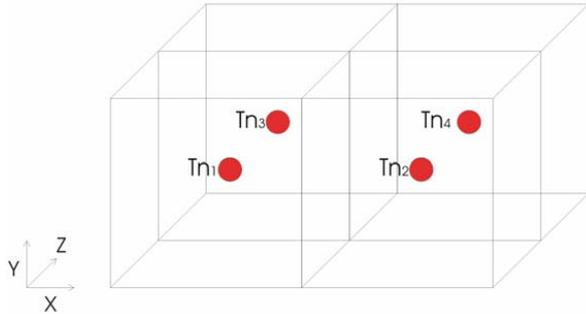


Fig. 3. Numbering of thermal nodes

$$\begin{bmatrix} [C_1 \ \lambda_1 \ x_1 \ y_1 \ z_1] & [C_2 \ \lambda_2 \ x_2 \ y_2 \ z_2] & \dots \\ \frac{N_{1x+}}{N_{1x-}} & \frac{N_{2x+}}{N_{2x-}} & \dots \\ \frac{N_{1y+}}{N_{1y-}} & \frac{N_{2y+}}{N_{2y-}} & \dots \\ \frac{N_{1z+}}{N_{1z-}} & \frac{N_{2z+}}{N_{2z-}} & \dots \\ [\alpha_{1x+} \ \alpha_{1x-} \ \alpha_{1y+} \ \alpha_{1y-} \ \alpha_{1z+} \ \alpha_{1z-}] & [\alpha_{2x+} \ \alpha_{2x-} \ \alpha_{2y+} \ \alpha_{2y-} \ \alpha_{2z+} \ \alpha_{2z-}] & \dots \end{bmatrix} \quad (13)$$

This structure is a special two-dimensional matrix. Columns contain data assigned to the elements of a thermal node with a given ordinal number in a format of a row vector, so the elements of the structure are vectors. The elements of the first row are the material parameters and geometric data assigned to the given thermal node. These data are sequentially C – thermal capacitance, λ – coefficient of heat conductivity, x , y and z – geometric sizes of the element. The next six rows contain the ordinals of the neighbouring nodes divided into rows per directions. The denotation of direction is shown by Fig. 4.

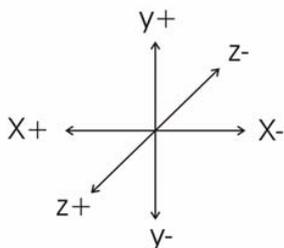


Fig. 4. Denotation of the directions

If the ordinal of the n^{th} node is included in one of the rows in the m^{th} column (in vector \underline{N}), then it means that the n^{th} node

is the neighbour of the m^{th} node from the specified direction, which direction is defined by position of the ordinal in vector \underline{N} . The vector in the last row contains the coefficient of heat transmission in six directions belonging to the specified element. For example, Eq. (14) shows the relations between neighbouring elements turning up in case of the four thermal node of Fig. 3 (other data assigned to the nodes are omitted).

$$\begin{bmatrix} [C \ \lambda \ x \ y \ z] & [\dots] & [\dots] & [\dots] & [\dots] \\ \frac{N_{x+}}{N_{x-}} & [] & 1 & [] & 3 \\ \frac{N_{y+}}{N_{y-}} & 2 & [] & 4 & [] \\ \frac{N_{z+}}{N_{z-}} & [] & [] & [] & [] \\ \frac{N_{x+}}{N_{x-}} & [] & [] & 1 & 2 \\ \frac{N_{y+}}{N_{y-}} & 3 & 4 & [] & [] \\ \frac{N_{z+}}{N_{z-}} & [\dots] & [\dots] & [\dots] & [\dots] \end{bmatrix} = \quad (14)$$

The method of description implies that the places of nodes in the mesh are not defined by the ordinal of the thermal node, but the relations between neighbouring elements.

4.2 Creation of the system of equations to be solved

If the descriptive structure above is made, a system of differential equation has to be created. This is based on Eq. (11) which is applied for each node. The system of equation is created according to Eq. (15), where the actual node is denoted by m and its neighbours are denoted by n .

$$\frac{dT_m(t)}{dt} = \sum_{\substack{x+, x- \\ y+, y- \\ z+, z-}} \sum_{\underline{N}_m} \frac{T_n(t) - T_m(t)}{C_m \cdot (R_m^n + R_n)} \cdot dt + \sum_{\substack{x+, x- \\ y+, y- \\ z+, z-}} \sum_{\underline{N}_m} \alpha_m^n \cdot \frac{T_{amb}^n(t) - T_m(t)}{C_m \cdot R_m^n} \cdot dt \quad (15)$$

where $T_m(t)$ is the temperature of the m^{th} thermal node in moment t , C_m is the thermal capacity of the m -th node, $T_n(t)$ are the temperature of the neighbours of the m^{th} thermal node selected according to the vectors, R_m^n are the thermal resistance of the m -th node in the direction defined by the vectors of \underline{N} , R_n is the thermal resistance of the neighbouring element defined by the vectors \underline{N} , α_m^n is the heat transmission coefficient in the specified direction, $T_{amb}^n(t)$ is the ambient temperature in the specified direction. The first term of the expression means that while sweeping through the elements of the six vectors of contiguity, the neighbours of the m^{th} element in the specified direction are selected and Eq. (11) is applied on them. The second part of the formula is applied to the elements, which have no neighbours, since they are located on the boundary of the region or they are in connection with gas. In this case Newton formula is used. Elements with no neighbours are denoted by \overline{N}_m . Let us define

multiplicators of temperature-change as follows. For the first part of the formula:

$$e_1 = \frac{1}{C_m \cdot (R_m^n + R_n)} \cdot dt \quad (16)$$

For the second part of the formula:

$$e_2 = \frac{\alpha_m^n}{C_m \cdot R_m^n} \cdot dt \quad (17)$$

The definition of multiplicators in the case of neighbours in direction x is the following:

$$e_1 = \frac{\min((y_n \cdot z_n), (y_m \cdot z_m))}{C_m \cdot \left(\frac{x_n}{2 \cdot \lambda_n} + \frac{x_m}{2 \cdot \lambda_m}\right)} \cdot dt \quad (18)$$

The numerator contains the calculation of the common surface of two neighbouring elements. The formula defines the surface of the common side in the case of both elements. The smaller value is considered, which is achieved by using the $\min()$ function. This examination is necessary, because the common surface can be defined, even if the elements have only one neighbour in the specified direction. The denominator contains thermal resistance, thermal capacitance of the specified thermal node and the thermal resistance of the neighbouring element. The multiplicator regarding heat transfer is calculated as follows:

$$e_2 = \frac{\alpha_m^n \cdot (y_m \cdot z_m)}{C_m \cdot \frac{x_m}{2 \cdot \lambda_m}} \cdot dt \quad (19)$$

This is consistent with the Newton formula. The calculation is very similar in the case of neighbours in directions y and z . The only difference is that the regarding geometric parameters are considered in the formulas.

4.3 Solution of the equation system

An advantage of the modelling tool in Matlab environment is that the solver algorithm does not have to be implemented; Matlab has built-in functions for this purpose. This solution could not be the optimal from the viewpoint of the time consumption of the simulation; because faster algorithms exist e.g. the Sincos transformation and many others [14]. The Matlab environment speeded up the development of the tool and the application of a well-manageable non-uniform mesh will reduce the number of equations, hence the speed of the simulation is not crucial. The system of equation created according to the method described above is written into an m-file. This m-file is the input of the solving functions of Matlab. The solution and the process of simulation are supported by functions `ode45()` and `ode23()`.

The `ode45()` is based on an explicit Runge-Kutta (4,5) formula, the Dormand-Prince pair. It is a one-step solver - in computing $y(t)$, it needs only the solution at the immediately preceding time point, $y(t-1)$. The `ode23` is an implementation of an explicit Runge-Kutta (2,3) pair of Bogacki and Shampine. It may be more efficient than `ode45` at crude tolerances and in the

presence of moderate stiffness. Like `ode45`, `ode23` is a one-step solver [16].

The solution of the equation system is fast and precise due to the built-in functions.

4.4 Application of a non-uniform mesh

Many practical task demands the compression or the rarefaction of the mesh on a part of the examined geometry [18]. The reason for this demand can be the inhomogeneity of the examined region, or the remarkable inhomogeneous distribution of the temperature calculated during simulation. Other common reason can be that a dense division is defined on one part of the examined region because of the prescribed accuracy, which implies that matrices with great number of elements and therefore a powerful hardware is needed. In this case it might be a solution, if the rarefaction of the thermal nodes is applied at least in a part of the examined region. The density of the applied grid is defined by the following:

- Material parameters – mesh is adaptable to the task
- Thermal gradient – mesh is to be changed during simulation
- User, manually – according to individual consideration

During the development of Matlab-based modelling tool, the variability of the density of the applied mesh was a basic requirement, the mesh in critical places, where the greatest thermal gradient occurs, should be dense compared to the size of the examined region. Non-uniform mesh density on a region is illustrated by Fig. 5. Individual functions support the change

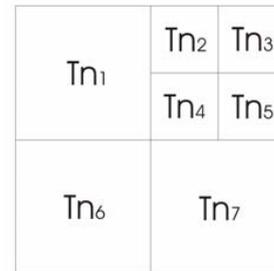


Fig. 5. Non-uniform mesh in 2D

of mesh density inside the modelling tool. The implementation of those functions is only a programming challenge due to the conformation of the structure, the local compression or rarefaction of the mesh is not more than modifying relations between neighbours, and increasing or decreasing the number of columns in the descriptive structure.

5 Modelling of thermal behavior of surface mounted components during reflow soldering

Reflow soldering is used for the attachment of surface mount devices (SMDs) to printed wiring boards (PWBs). The reflow oven heats the entire assembly to a temperature exceeding the

melting point (reflow temperature) of the solder alloy. This allows melting the individual solder particles in the paste into a single drop, which can wet the PWB pads and component leads or metallizations to form solder joints. Heating of the assembly is achieved by an oven containing several independently controllable heating zones [11].

The heat transfer to the assembly is typically achieved by forced convection method. Nevertheless the thermal conduction is also important for the exact description of the process because the heat spreads inside the components and within the PWB. The conduction properties of the large-size components usually are not homogeneous and due to their mass their effects are considerable (Fig. 6). Therefore the conduction properties also play important roles in the formation of the thermal distribution at the level of the components. Hence inhomogeneous thermal distribution can appear within the components too. This effect could explain unexpected reflow soldering failures [19].

As mentioned in section 2., numerous thermal modelling tools exist, but unfortunately in this case they cannot be applied. In the case of the reflow soldering, the conditions are very different opposite to e.g. the examination of a dissipation of active elements. During the reflow soldering the heat comes from the outer side of the package, the coefficient of the heat transmission between the gas and the component is varied in the function of time and place ($f(t, r)$). The thermal distribution of the PWB – it can be very inhomogeneous – plays also important role. The whole process is non stationary, and the melting of the solder paste (from solid into liquid state) may take also strong influence on the thermal distribution.

5.1 Test of the modelling tool

In this section an example, modelling of heating up a TO package with forced convection is presented, which shows the proper function of the Matlab-based modelling tool. The structure of the TO package can be seen in Fig. 7. Epoxy forms the body of the package, the silicon chip can be found in the middle, the leads and the chip carrier are prepared by copper.

At the first examination, a simplified geometry is applied in the simulation: the leads were neglected and the chip carrier was replaced by a brick-shaped body. The simplified geometry can be seen in Fig. 7. On the top of the geometry a boundary condition was applied equivalent to a heated gas-flow. The thermal distribution of the geometry was investigated by a FEM software and by the aid of the Matlab-based tool as well to compare the software together.

The results for moderate heating (45 K) can be seen in Fig. 8. The temperature of the right-hand upper corner of the component is shown in function of time. Although the way of the solution is completely different, it can be seen; that the calculated results are almost identical.

6 Conclusion

In this paper a method was presented for modelling temporal and spatial temperature distributions of modules during the reflow soldering process. The basic considerations and the mathematical structure of the model were described. The accuracy of the calculations was successfully tested by comparison with standard finite element method at moderate temperature region.

The main advantages of our model are the capability for calculations in extended temperature ranges above the melting point of the solder paste, the easy modelling of more complex electronic structures (PWBs) and simple development options for additional physical effects.

Using our method inhomogeneous thermal distribution can be calculated around and within electronic components on the PWBs. This effect can explain unexpected reflow soldering failures.

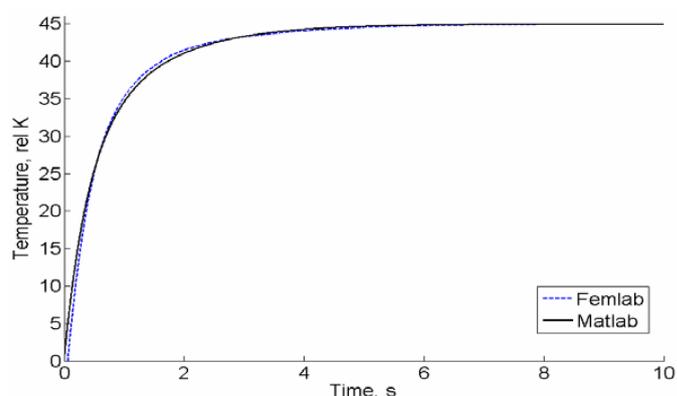
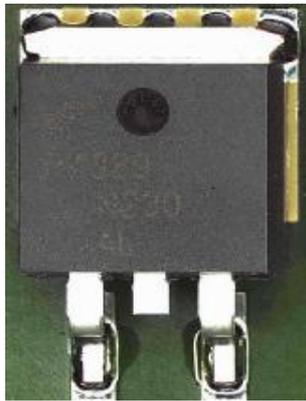
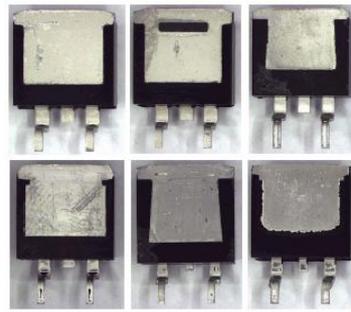


Fig. 8. Comparison of the Matlab-based tool and the FEM model

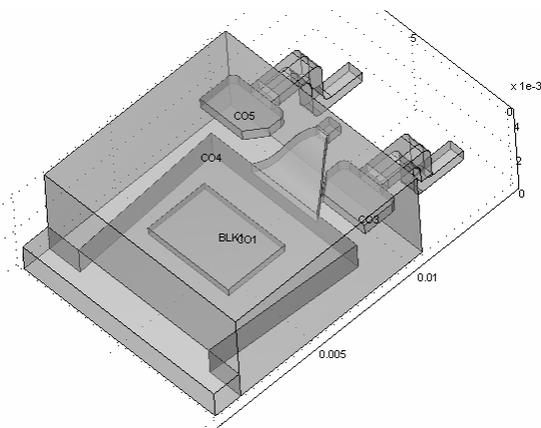


a)

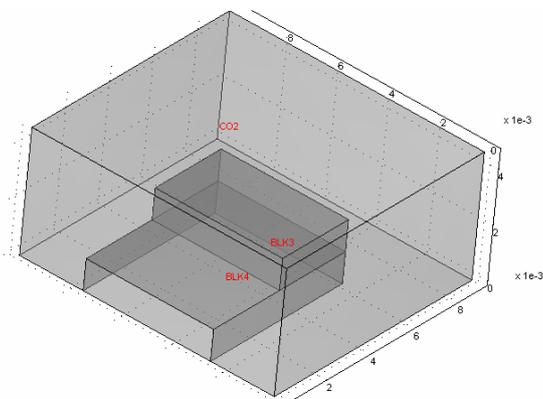


b)

Fig. 6. Examples of large-size SMD components, TO packaged power components



a)



b)

Fig. 7. a.: Structure of TO package, b.: Simplified TO package

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