# NUMERICAL MODELING OF THERMAL REGIMES DURING THE ASSEMBLY OF A MULTICOMPONENT SYSTEM

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Results are presented from a numerical modeling of the solution of a problem involving optimization of the thermal regime in the assembly of integrated circuits. The modeling was performed on array processors of hybrid computers.

By mathematically modeling the nonstationary temperature fields of large-scale integrated circuits (LIC) in ceramic packages when the latter are being soldered to the circuit boards, it is possible to optimize the assembly operation. The control functions might be the temperature or the velocity of the heating gas during soldering or the heating scheme. The heating time depends not only on the temperature of the heating gas ($T_g$), but also on the direction of the gas jet (upward, downward, upward and downward) and the temperature of the system during preheating. Selecting optimum control functions makes it possible to minimize heating time, which in turn significantly increases the productivity of the assembly line. At the same time, sufficiently accurate and complete representation of the temperature fields makes it possible to calculate the thermal stresses and strains in the elements of a large system of electronic devices while it is being assembled (see Fig. 1).

A segment of the solder 6 is first applied to the contact area 5 of the printed circuit board 7. During heating, the solder is to join the contact area 5 of the LIC package with the contact area 5 of the board. The solder partially fuses and the device settles under its own weight. The elements of the system are heated by gas supplied from above ($T_{g1}$, $\alpha_{\Sigma 1}$), from below ($T_{g2}$, $\alpha_{\Sigma 2}$), and into the slit between the board and the LIC ($T_g$, $\alpha_\Sigma$). As already noted, the heating scheme and preheating can change the soldering time and the reliability of the joint.

The momentary increase in the temperature of the crystal 3 (Fig. 1) should not exceed 250°C. The heating time should be minimal, in order to ensure a reliable joint and tolerable thermal stresses. The heating time also partially determines the productivity of the LIC assembly line. Since full-scale production tests cost several times more than computational experiments, we developed a method of calculating the temperature fields created during product assembly.

The time available for the numerical experiment was limited. In light of this, we chose to conduct the experiment using an array processor (an electrical model of variable resistors) of a hybrid computer designed especially for the solution of heat conduction problems. The study [1] described a relatively simple method of solving nonlinear volumetric problems of nonsteady heat conduction on electrical models. The solution of the problem on an array processor takes less time than the writing and debugging of a program for a general-purpose digital computer. We want to make it clear that we do not yet have a finished application package for solving problems similar to the problem formulated here.

In the mathematical modeling, we solved direct and inverse problems involving determination of criteria of nonambiguity and refinement of the model (parametric and structural identification). After the model was refined, we solved problems entailing the optimization of heat conduction. These problems are termed structural calculations in engineering practice and "thermal design" in computational thermophysics.

The first step was to use data from thermal experiments reflecting the above-mentioned production processes to evaluate the coefficients of heat transfer from the heating gas in the slit to the solder. The solution of such external inverse problems required the prelimi-

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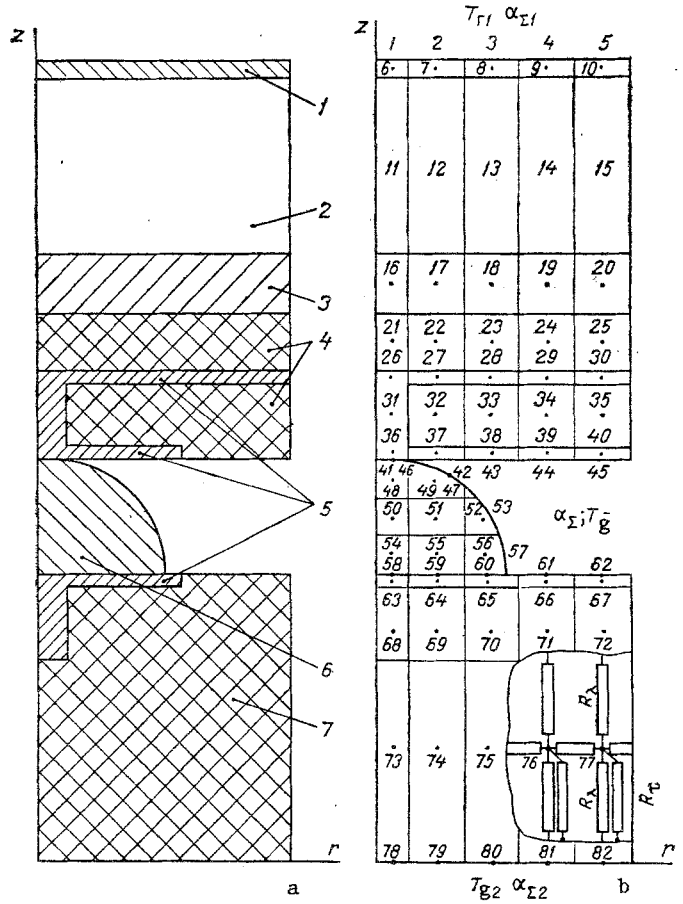


Fig. 1. Thermal scheme of an LIC–solder–board system during assembly up to the beginning of melting of the solder (a) (1 – cover of the LIC; 2 – air space; 3 – crystal; 4 – LIC package; 5 – contact areas, metallization; 6 – solder; 7 – printed circuit board) and subdivision into space intervals, fragment of an R–R circuit (b).

nary solution of procedural problems involving optimization of the elementary spatial volumes and time intervals, selection of the method to be used for electrical modeling of solidification (fusion) problems [2-4], and development of a method of changing the circuit region with allowance for the change in the form of the melting solder.

The mathematical model of the temperature fields in the elements of the system has the form

$$\frac{\partial}{\partial x_i}\left[\lambda(T)\frac{\partial T}{\partial x_i}\right]-c_V(T)\frac{\partial T}{\partial \tau}=0, \quad i=1,\ 2,\ 3, \tag{1}$$

for the three-dimensional problem.

The main transport equation (1) is written for all elements of the system. The array processor – the R–R circuit electrical model – makes it possible to connect parts of the model for which the corresponding parameters of the circuit were calculated on the basis of different coordinate systems. In our case, a spherical system is used for the solder and a cylindrical system is used for the other parts. For that part of the system located sufficiently far from the edges of the integrated circuit, it is possible to solve two-dimensional problems with allowance for the symmetry of the temperature fields.

The boundary conditions are of types II-IV, considering all of the solution variants. For example, for the bottom plane (Fig. 1) in the case of heating only from above, (we assign boundary conditions of type II ($q_s$ = 0) instead of type III ($\alpha_{\Sigma 2}$, $T_{g2}$). At those sites and in those cases when contact thermal resistances are possible, instead of conditions of ideal contact

$$T_{s1} = T_{s2}, \tag{2}$$

$$T_{s1} = T_{s2} + \Delta T_c \quad \Delta T_c = R_c q, \tag{3}$$

we assign conditions of nonideal contact. Then instead of conditions (2) we have the condition

$$T_{s1} = T_{s2}, \tag{4}$$

where $R_c$ is the contact thermal resistance. In such cases, instead of (2-4) we assign

$$-\lambda_1 \frac{\partial T}{\partial n}\Big|_{s1} = \frac{1}{R_c}(T_{s2} - T_{s2}). \tag{5}$$

Equation (5) corresponds to the form in which type III boundary conditions are assigned when the temperatures $T_{s1}$ or $T_{s2}$ are regarded as temperatures of the environment $T_e$ (for example, $T_{s1} = T_e$), while that part of the component body with the surface $T_{s2}$ is considered to be a body undergoing external heat transfer with type III boundary conditions. In essence, such a transition entails isolating each body separately in a system of bodies, i.e., regarding other bodies in contact with the given subsystem being studied as an external medium.

In our case, type IV boundary conditions include the case of Stefan conditions, when nonideal contact is formalized as

$$-\lambda_1 \frac{\partial T}{\partial n}\Big|_{s1} = \lambda_2 \frac{\partial T}{\partial n}\Big|_{s2} \tag{6}$$

but

$$-\lambda_1 \frac{\partial T}{\partial n}\Big|_{s1} = -\lambda_2 \frac{\partial T}{\partial n}\Big|_{s2} + L\rho \frac{\partial \Pi}{\partial \tau}. \tag{7}$$

In this case, the internal ($q_V$) or surface ($q_S$) heat sources depend on the heat of the internal transformations, which can be accounted for either as $q_V$ and $q_S$ or in the effective volumetric heat capacities – $c_{Vef}$. A method of accounting for the heat of internal transformations was described in detail in [3]. V. K. Mel'nick participated in the studies whose results are reported below. The main feature of the problem briefly described above is the changing form of the integrated circuit–solder–printed circuit board system. As fusion proceeds, the circuit "settles" while the amount of solder present remains the same. However, the form of the solder changes: it is transformed from a segment (nearly a half-sphere) into a disk with somewhat rounded edges.

Depending on the variant of the overall problem, the initial conditions can be assigned either in the form of a uniform temperature distribution equal to 293 K or a nonuniform distribution with allowance for the initial heating of the entire system.

To solve external inverse problems and heat-conduction optimization problems, we used the selection (sampling) method described in [5]. The method involves error minimization based on allowance for values of functions describing the sensitivity of the model to changes in the sought control functions. In contrast to numerous studies of methods of solving inverse problems, the initial data was not simply test temperatures but the time during which melting occurred on physical models.

Everywhere where type III boundary conditions were assigned, the heat-transfer coefficients were additive $\alpha_\Sigma$ and nonlinear, i.e.

$$\alpha_\Sigma(T_e, T_s) = \alpha_c + \alpha_r \tag{8}$$

where $\alpha_c$ and $\alpha_r$ are the convective and radiative heat-transfer coefficients, respectively. The values of these coefficients depend on the temperature of the external media $T_e$ and the surfaces $T_s$.

By solving a series of unidimensional and two-dimensional problems of solidification (fusion), we studied the effect of a number of factors, which can be termed methodological, computational, and thermophysical.

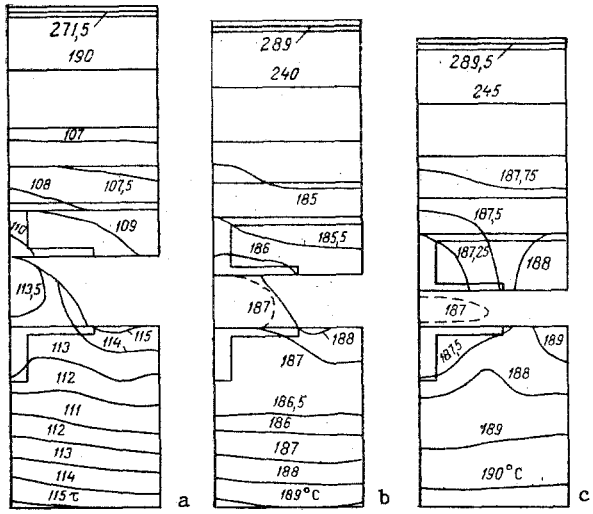


Fig. 2. Temperature distribution in the system during assembly: a) $\tau$ = 5 sec; b) 12; c) 13.

The methodological factors were as follows. The solidification problem can be solved with an array processor of a hybrid computer by using several different methods of assigning the heat of the internal transformations: 1) with the use of effective heat capacity $c_{Vef} = (c + L_{sp})\rho$, where $L_{sp} = L/(T_\ell - T_s)$; 2) with the introduction, at the nodes, of currents which model the heats of the internal (phase) transformations; 3) with the introduction of such currents at any point of the circuit at which the melting point is attained. These methods can be conditionally designated as $\Lambda c_{Vef}$, $\Lambda R_q$, $\Gamma R_q$, where $\Lambda$ represents Liebmann's method [1] and $\Gamma$ represents Gel'perin's method [2].

The computational factors include: 1) the values of the space and time intervals; 2) the location of the nodes relative to the boundaries of the elementary volumes; 3) the number of dimensions of the finite difference grid; 4) the range of "diffuse" temperatures $(T_\ell - T_s)$, since in our problem $T_\ell = T_s = T_L$.

The thermophysical factors include: 1) L; 2) the thermal properties of the board; 3) $R_c$; 4) the magnitudes of the heat sources and their location; 5) the initial temperature of the system.

The effect of most of the above factors was studied in order to refine the mathematical model, which was then used as the initial model in a problem involving optimization of control of the assembly operation.

The method $\Gamma R_q$, with the location of the nodes on the boundaries of the elements, provides the greatest accuracy relative to approximate analytic solutions. This was confirmed by data obtained in [3] for problems similar to those being considered here. Use of the method $\Gamma R_q$ makes the diffuse temperature range dependent on the time intervals – which were chosen to be optimal.

An analysis of the solutions of the direct and inverse problems showed the following. The most efficient approach is to use a nonuniform grid with a refined movable part in the region of the phase front.

Solution of an inverse problem involving optimization of the actual time of the soldering process yielded the range of possible values $\alpha_{\Gamma\Sigma}$ = (250-300) W/(m$^2$·K).

It was established that with an increase in L (from 47,000 to 60,300 J/kg), the time corresponding to the beginning of melting increases from 3 to 9 sec. Thus, the time of heating of the entire system and its temperature in the hazardous zone depend appreciably on the exact value of L, i.e., it is desirable to select a solder with a minimum value of L (if this is possible). In optimization, it is necessary to use values of L which are as accurate as possible. The thickness of the board has a considerable effect on the fusion time, doubling the period over which melting occurs. The presence of contact resistances between the solder and the board typically shortens the time corresponding to the beginning of melting and the time required for complete fusion. This nontrivial result cannot be obtained a priori, since these times depend appreciably on the thermophysical characteristics of the material and the

assembly technology. This conclusion substantiates the proposition that the thermal system being studied here need not be regarded as a large system. New properties are created in the system due to the coupling of the subsystems.

Bidirectional heating and an increase in the initial temperature reduce the time corresponding to the onset of melting and the duration of the melting period in the absence of an air space (see Fig. 1). The presence of an air space weakens the effect of top heating, while an increase in the critical temperature in the crystal region during fusion does not necessitate allowance for top heating. The temperature in the critical region increases negligibly due to the air space and is determined mainly by the bottom heating. An increase in the initial temperature substantially shortens the melting period, but the temperature in the critical region still increases to the limitingly allowable value. Thus, to shorten the assembly operation, it is best to first preheat the entire system. In optimizing the system, it is possible to optimize the initial temperature so as to minimize assembly time while observing the prescribed thermal conditions in the crystal region. Simultaneously increasing the initial temperature lowers the temperature gradients, which in turn reduces the thermal stresses and strains. Figure 2 shows the temperature distribution obtained by solving the two-dimensional problem. The array processor allowed us to replace the solder by a grid calculated for a spherical coordinate system and the remaining elements by a grid for a cylindrical coordinate system. It is evident from the figure that the contact areas change the temperature fields considerably. The thermal regimes for such structures cannot be optimized on the basis of unidimensional models. To allow for the change in the form of the solder, the calculations must be performed on a grid with movable boundaries. This is because the heating areas in the solder zone change appreciably on the side of the gas entering the slit.

Thus, array processors of hybrid computers make it possible to perform complex calculations and optimize thermal processes in thermal systems. Analysis of the temperature fields in such systems shows that given specific ratios of the parameters of numerical models, it is possible to obtain results for such systems having the properties of large systems. In other words, a system's approach is needed for structures such as those discussed here. This type of approach is impossible when the model simplifications normally used in engineering thermophysics (linearization, transition to unidimensional problems, deformation of the model, etc.) are employed.

## NOTATION

$T_g$, gas temperature; $\alpha$, heat-transfer coefficient; $c_V$, specific heat capacity; $\lambda$, thermal conductivity; $\tau$, time; q, heat flux; L, internal heat of phase transformations or other internal transformations; $c_{Ve}$, effective volumetric heat capacity; $\rho$, density; $q_V$, power of internal heat sources; Indices: g, gas; c, convection, contact; sp, spectral; r, radiative; L, phase transformation; V, volumetric; 0, initial; e, environment; $\ell$, liquidus; s, solidus; s, surface; $\Sigma$, total. Abbreviations: R–R, resistance circuit; $\Lambda$, Liebmann method; $\Gamma$, Gel'perin method.

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