Global/Local Heat Conduction and Thermomechanical Analyses of Multichip Modules

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Abstract

This paper presents a global/local analysis procedure for multichip modules. The global heat conduction and thermomechanical analysis procedures are based on a variational approximation procedure that produces a final system independent of the number of layers. The local heat conduction analysis employs a fast floating random walk method. The local thermomechanical analysis employs automated adaptive finite element modeling techniques. The application of this system to a 25 chip multichip module is demonstrated. Finally, adaptive techniques for controlling multiscale analysis errors are discussed.

INTRODUCTION

The effective design of a multilayer multichip module must account for its thermomechanical response to ensure the integrity of the device. A multilayer multichip module (MCM) is characterized by having a number of layers containing wires and vias in various configurations, in conjunction with a general chip and cooling structure layout. Failures caused by the thermomechanical loads are dictated by behaviors at the physical scale of the wires and vias. Although a micromechanical level analysis model representing all the features in a MCM could be used to determine failure parameters, the computational effort required for such an analysis would be prohibitive. An alternative is to employ a set of coordinated multiple scale analysis procedures to determine the critical parameters.

The next three sections of this paper discuss a system specifically designed for the global, and local, heat conduction and thermomechanical analysis of MCM's. The global analysis procedures employ averaging techniques to convert each layer into an equivalent homogeneous medium, while the local analyses consider the full microstructure in a small local area of the MCM. Both the global heat conduction and thermomechanical analysis procedures use a specialized variational method with global shape functions [1, 2]. The local thermal analysis employs a fast floating random walk method [3]. The local thermal stress analysis employs automated adaptive finite element modeling techniques [4]. The following section overviews the procedures used to automatically construct the three analysis model idealizations and discretizations used by the global and two local analysis procedures. This is followed by a section demonstrating the application of these procedures to a 25 chip MCM.

The last section discusses a method for the development of two scale analyses in which adaptive procedures based on estimates of both discretization and physical scale selection errors are outlined. These procedures, which have been applied to high performance composite materials, could potentially be applied in the analysis of MCM's.

GLOBAL/LOCAL ANALYSIS PROCEDURES FOR MULTICHIP MODULES

The basic idea of a multiscale analysis is to analyze the physical problem of interest with two or more levels of physical idealization. In the procedures considered in this section, two levels of physical idealization are considered. In the first level, the global level, each layer of the MCM is considered to be a homogeneous material with the physical parameters for each layer determined by an averaging of the properties of the individual components in that layer, the microstructure, such that the overall behavior of that layer can be predicted. In the second level the full details of the microstructure are considered in particular areas of local interest. A key issue in the development of multiscale analyses is the interactions of the global and local scales.

In a basic global/local procedure the global analysis is performed first. The results of the global analysis are then used as boundary conditions for the local analysis where the wires, vias, etc. are fully represented. In the present study, both the global and local analyses employ basic continuum models to provide a mathematical description of the heat conduction and thermomechanical behavior. In addition, it is assumed that the heat conduction and thermomechanical problems are uncoupled.

The global analysis procedures are based on a variational technique in which the differential equations and certain interface and boundary conditions are satisfied exactly. Therefore, the numerical solution process must only perform area integrals, as opposed to full volume integrals and the number of unknowns in the procedure does not increase as the number of interconnect layers increases. See references [1, 2] for a description of the specific procedures developed for the global heat conduction and thermomechanical analysis of MCM's.

The global heat conduction analysis is the first analysis performed. It produces an overall temperature field which is used by the global thermostress analysis and the local thermal analysis. The global thermostress analysis is the second analysis performed. This analysis directly uses the temperature field generated from the global heat conduction analysis to calculate the appropriate thermal strain field. The global thermostress analysis produces both an overall displacement and stress field. Information from the overall displacement field is used to specify boundary conditions in the local thermomechanical analysis.

The local heat conduction analysis is performed using a highly efficient stochastic algorithm for solving Laplace's equation [3]. The algorithm is based on the floating random-walk method [5, 6]. Briefly put, the algorithm derives from the Laplace solution on a scalable cubic domain, subject to arbitrary Dirichlet conditions. A boundary-integral solution is then found, from which an integral for temperature at the domain center is obtained. This integral is expanded as an infinite sum, and probability rules that statistically evaluate the sum are deduced. These rules define the algorithm, yielding the temperature at a specific point within the windowed local heat conduction domain. The Dirichlet boundary conditions are obtained from the global heat conduction analysis over the window boundary.

The boundary conditions needed for the local heat conduction analysis are obtained by the interrogation of the temperature field obtained in the global heat conduction analysis at the appropriate boundary locations. Since the local thermomechanical analysis requires the temperature values at the nodes of the finite elements within the three-dimensional analysis window, a procedure has been developed to efficiently evaluate the temperature at any requested location, given the point-to-point temperature values from the above stochastic algorithm. The local domain is divided into large rectangular parallelpipeds and a finite-term linear and trigonometric ??modal?? expansion is applied within each parallelpiped. The expansion functions exactly satisfy Laplace's equation within each parallelpiped. Expansion coefficients are then evaluated by sequentially fitting to temperature values (from the stochastic algorithm) at specific corner, edge, and surface points of all the parallelpipeds in the windowed local domain.

The local thermomechanical analysis employs automated adaptive finite element methods [4]. In this approach the finite element meshes are automatically generated for the detailed geometric representation in the local area under consideration.

The main components of an automated adaptive finite element procedure are:

1. an automatic mesh generator that can create valid graded meshes in arbitrarily complex domains
2. finite element analysis procedures capable of solving the given physical problem
3. a posteriori error estimation procedures to predict the mesh discretization errors and to indicate where it must be improved
4. mesh enrichment procedures to update the mesh discretization

Automatic mesh generation and mesh enrichment is performed by the Finite Octree mesh generator [7]. With an initial mesh generated, the finite element analysis is performed by the general purpose commercial finite element package ABAQUS [8]. The error estimator then calculates the solution error and determines where, and by how much, the mesh is to be refined or coarsened. This information is then used by the Finite Octree mesh generator to enrich the mesh for the next analysis step. This process is continued until the solution accuracy is deemed accurate enough.

The local thermomechanical analysis obtains displacement boundary conditions from the global thermomechanical analysis and a temperature field from the local heat conduction analysis as indicated above.

MODEL GENERATION AND CONTROL FOR MULTICHIP MODULE ANALYSIS

All numerical analysis procedures employ a discrete representation of the domain of the artifact being analyzed. This discrete representation is different for different numerical analysis methods. In all cases the required discretizations must be generated from the available physical description of the domain. Since the generation of the discrete numerical analysis models and controlling the interaction between them can dominate the cost of an analysis process, fully automatic numerical analysis discretization generation procedures are employed. The use of automated discretization procedures requires that a unique representation of the geometric domain, with respect to the discretization process, be available.

Consideration of the design and manufacturing representations employed for MCM's indicates that one commonly used domain description is a CIF file [9, 10]. Although convenient, a CIF file does not represent a complete and unique geometric representation of the non-manifold geometries [11] of an MCM. Therefore, the approach taken was to use the CIF file, attributed with a limited amount of additional information, as the basis of the MCM's physical description, and to develop software procedures to interpret the CIF files to provide the information needed by the automatic analysis discretization procedures used with the analysis procedures.

Since the analysis procedures employ different forms of numerical analysis discretizations, specific procedures were developed to support the global analysis procedures, the local heat conduction analysis procedure and the local thermomechanical analysis procedure.

The global heat conduction and thermoelastic analyses employ a layerwise discrete representation of the overall interconnect configuration, where each layer is assigned the appropriate averaged material properties. The procedure to determine this information employs the information in the CIF and attribute files. The other input information required is the size and position of the chips on the top surface of the MCM.

Figure 1 graphically depicts the process of constructing the global idealized analysis model. Starting from the discrete entity information in the layers of the CIF file, the appropriate set of layers to receive averaged properties is determined. The averaged material properties are constructed based on the percentages of each material in the layer. Consideration of the effect of the vias differs between the heat conduction and thermostress analyses. Since the thermal vias can account for a major portion of the vertical heat transfer, specific consideration of their influence in considered in the heat conduction analysis.

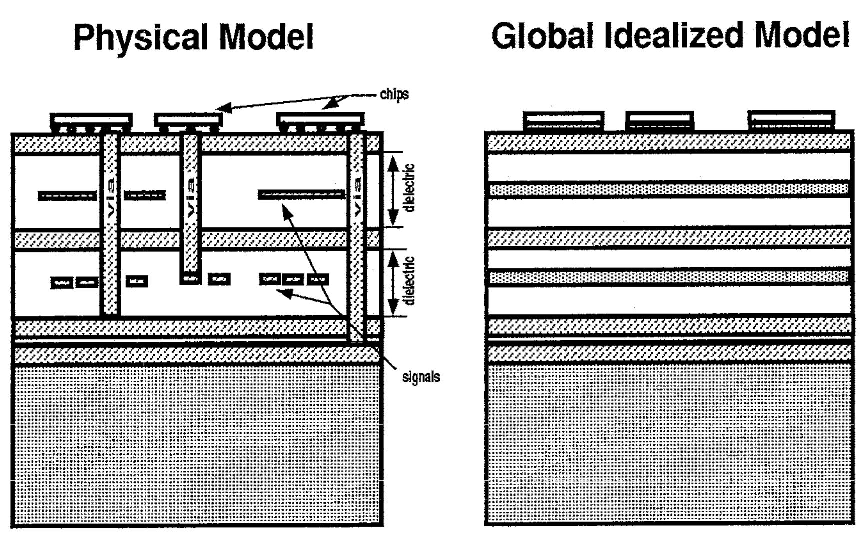


Figure 1. Two-dimensional depiction of constructing the global analysis model from the physical description of the MCM.

The numerical analysis discretization for the local heat conduction analysis requires a decomposition of the local volume into a set of materially uniform rectangular parallelpipeds. Each parallelpiped is characterized by its pair of body-diagonal endpoints and its thermal conductivity.

Geometric and material data for the local heat conduction analysis are received in a (mask-level) CIF format. Layer thicknesses, wire thicknesses, and corresponding thermal conductivities are extracted for the analysis attribute information. Parallelpiped blocks of uniform composition are generated by a simple layer-by-layer parsing of the CIF data based on the parallelepiped entities in the file.

A major reason for selecting finite element methods for the local thermomechanical analysis is to allow for full discretizations of the local microstructure geometry. The finite element discretizations are automatically constructed using the Finite Octree mesh generator [7] which requires that the domain to be analyzed be defined within a solid modeling system which supports the required geometric interrogations. Since the CIF file only contains the basic geometry defining the interconnect, it is incapable of supporting the required geometric interrogations. Therefore, a procedure was developed to build, from the information in the CIF file, the non-manifold solid model of the local geometry in a geometric modeling system that can support the mesh generator's geometric interrogations. In this project the Parasolid [12] solid modeling system, with the proper non-manifold extensions for multiple material domains, has been used.

The procedure used to generate the multiple material solid model in an extended solid modeling system starts with a CIF file containing a 2–D description of the MCM layers in terms of rectangles, polygons, circles, and paths. When attributed with a thickness parameter, each such CIF entity can be formed into an appropriate solid primitive in the solid modeling system. The primitives of a single material type are unioned to form the collection of solid bodies of that material type. The solid bodies of the different material types are then combined using special multi-material Boolean operations to build the final multi-material solid model of the local region of the MCM microstructure. Figure 2 shows a Parasolid model in the vicinity of a chip on an MCM, and a local window which is of the size used in the local thermomechanical analysis.

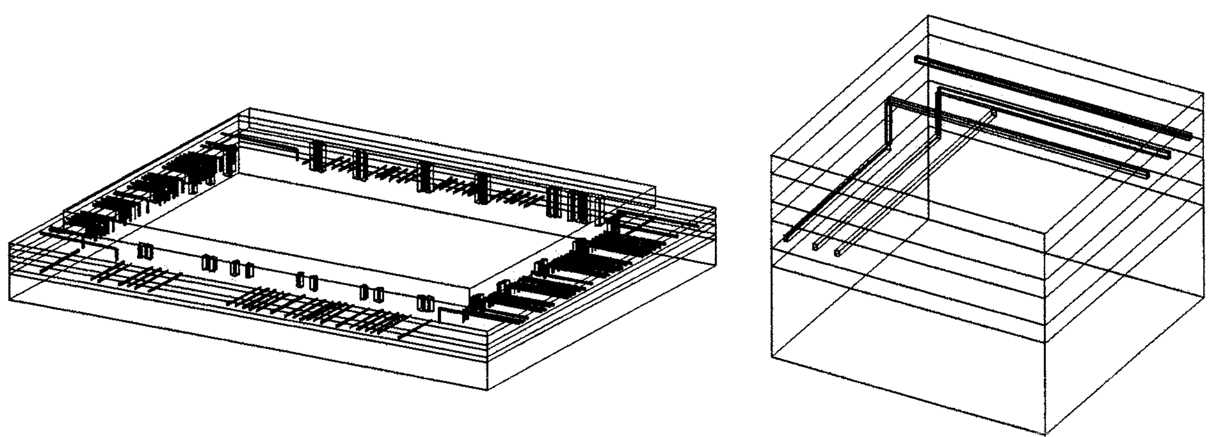


Figure 2. Views of a Parasolid model of a simple one chip interconnect created from a CIF file.

Since the local finite element analysis procedure is intended to consider only a small local portion of the MCM in an analysis, the procedure to construct the local non-manifold solid models has been extended to efficiently build the non-manifold solid only within a prespecified rectangular parallelepiped. This construction is easily supported by first intersecting each primitive of the

CIF file with the given parallelepiped before performing the required union operations. To make this process computationally efficient, CIF file entities that do not interact with the selected parallepipeds are not included in the primitive construction and Boolean operation processes. For example, layers with z-values that do not overlap the parallelepiped need not be considered, while entities in layers that do not overlap the xy-rectangle of the parallelepiped need not be considered.

APPLICATION OF GLOBAL/LOCAL ANALYSIS PROCEDURES TO A TWENTY FIVE CHIP MULTICHIP MODULE

Figure 3 shows the chip layout of a 25 chip MCM. This interconnect has an 11 layer structure which is shown in figure 4. As an example of the results of the global analysis procedures, figure 5 shows contours of the temperature field predicted by the global heat conduction analysis. As expected the temperature is highest directly under the chips with the highest power density and the temperature field shows a lateral diffusion as the vertical distance from the top surface increases. The global thermomechanical procedure is then used to predict the stresses due to the deformations caused by this temperature field. The stress results show similar patterns of distribution due to the uniform essential boundary conditions, and the fact that the material properties are averaged over each layer.

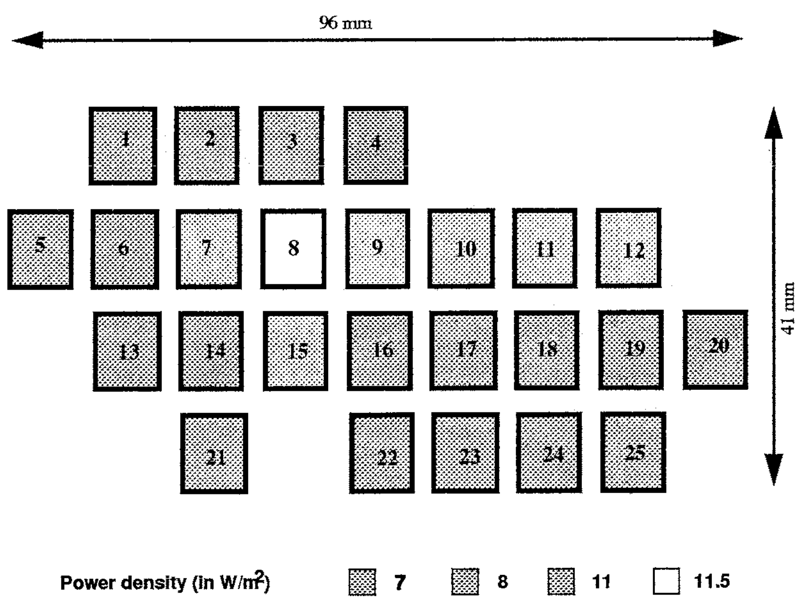


Figure 3. Layout and power density of chips for the F-RISC/G processor interconnect.

The local heat conduction is performed on the local window shown in figure 6. Figure 7 shows the temperature field predicted on the four planes that are shown shaded on the local window (Fig. 6). As expected, the wires tend to act as heat conduits, and therefore cause higher temperature in the immediate vicinity of the wire.

Using the temperature from the local heat conduction analysis and boundary displacements predicted by the global thermomechanical analysis, the local thermomechanical analysis is conducted. Figure 8 shows the initial automatically constructed coarse mesh, the stresses

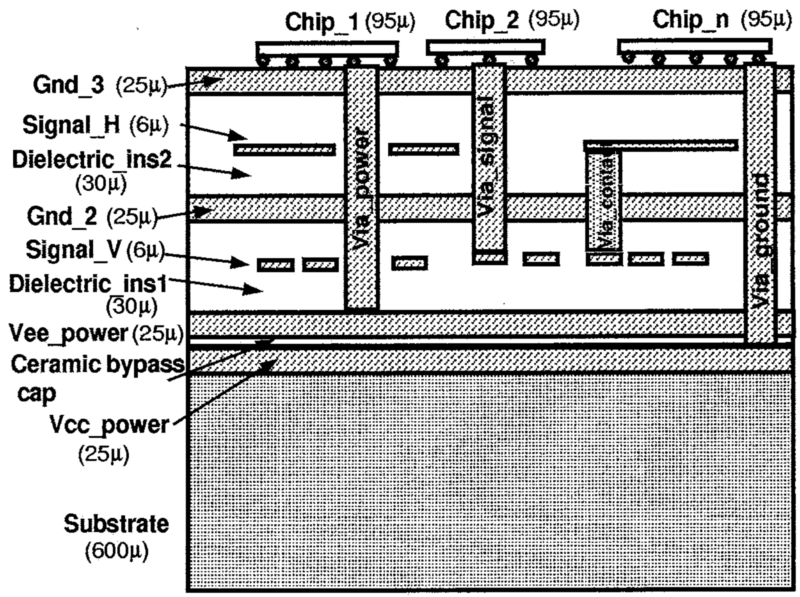


Figure 4. Arrangement of layers for the F-RISC/G processor interconnect.

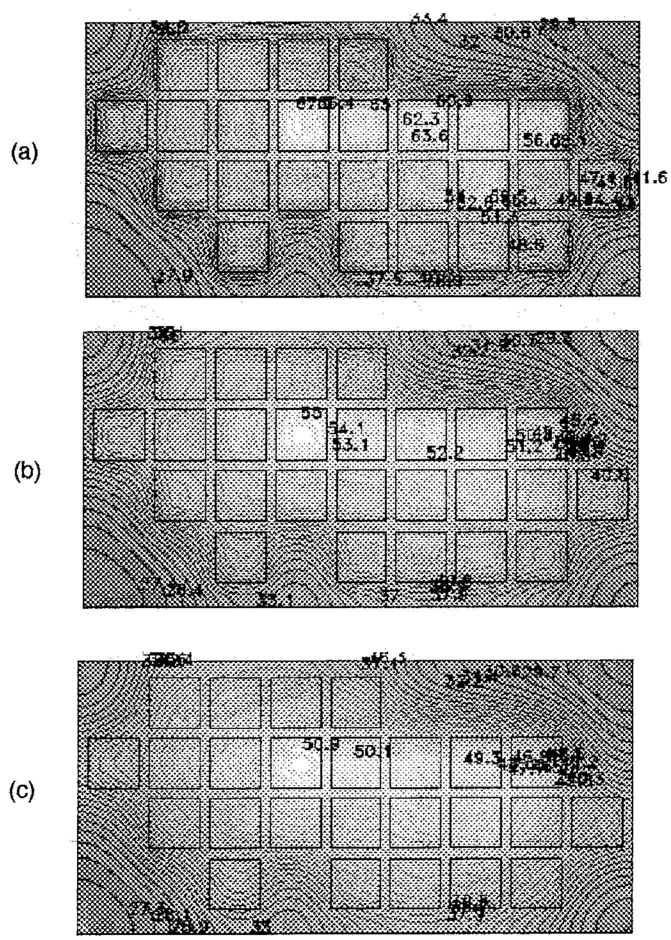


Figure 5. Temperature field predicted by the global heat conduction analysis procedure in (a) the top layer GND_3, (b) the X-signal layer Signal_H, and (c) bottom layer Substrate

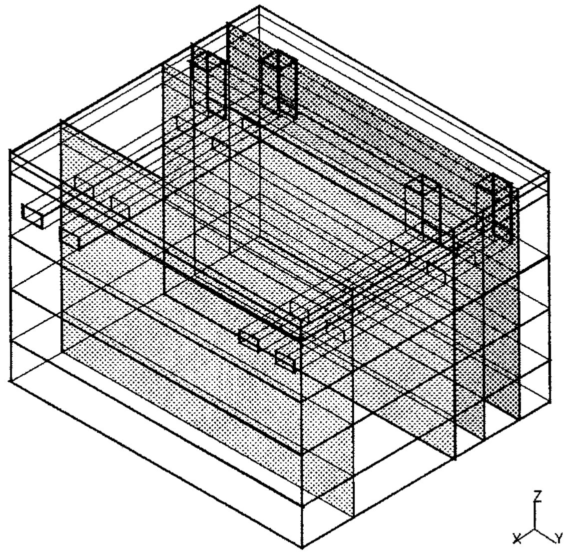


Figure 6. Windowed region of the interconnect used in the local analyses (the shaded planes indicate the planes for which local temperature results are presented).

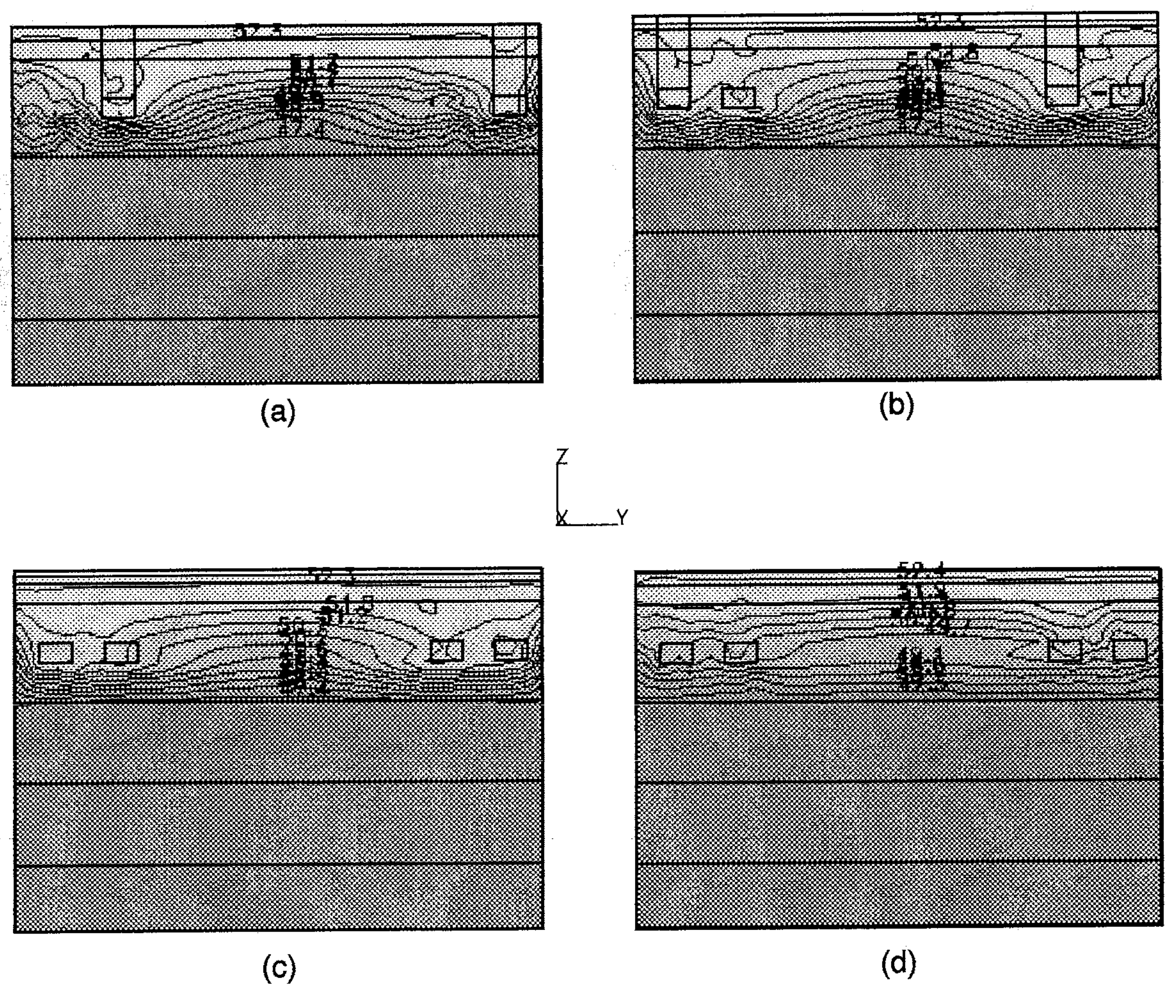
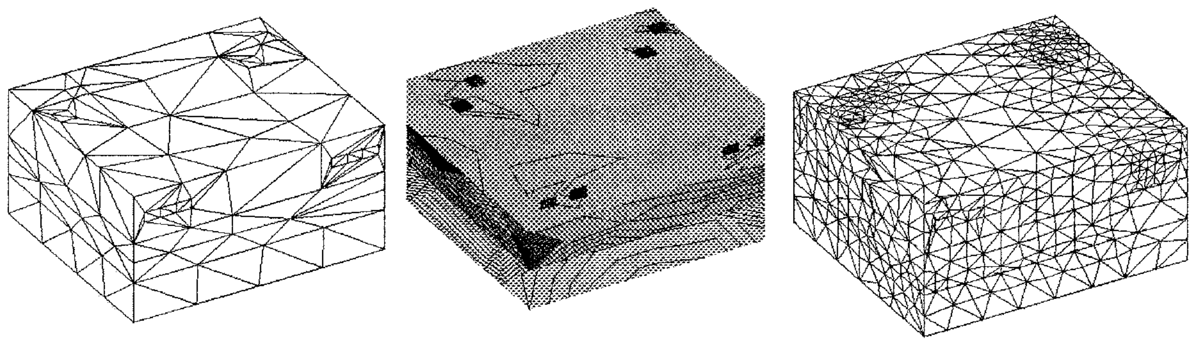


Figure 7. Temperature field predicted by the local thermal analysis on the four selected planes.

predicted on this coarse mesh, and the adaptive refined mesh automatically constructed for the local window. A careful examination of the results indicates high stress concentrations at the intersection of wires and vias. Since the local details of the geometry in these regions has a strong influence on the stresses predicted, an important future improvement is to replace the current right angle blocks with smoother shapes more consistent with that which is actually produced during the deposition processes.



(a) (b) (c)

Figure 8. Local thermomechanical analysis, (a) is the initial mesh, (b) the stresses predicted on the coarse mesh, and (c) the adaptively refined mesh.

ADAPTIVE MULTISCALE ANALYSIS TECHNIQUES

An important aspect of automated analysis procedures is the explicit control of the analysis errors introduced. Although the procedures presented in the previous sections do provide a seamlessly integrated automated analysis tool, they do not provide explicit control of all analysis errors. The only contribution to the analysis error controlled in the procedure presented is the discretization error associated with the finite element mesh. Even if explicit discretization error control were added for each of the analysis procedures, there are still potential errors associated with the use of a simple global/local analysis procedure in which the local analysis simply accepts the boundary conditions predicted by the global analysis as being correct. To control this source of error, there needs to be an explicit coupling of the global and local solution procedures. Such a coupling is reasonably straight forward when both the global and local analysis procedures solve the problem on the same physical scale. However, when two differernt physical scales are used, in this case an averaged macromechanical scale and detailed micromechanical scale, the efficient coupling and error control between these two scales is more complex.

The two common approaches for effectively controlling errors when the analysis considers two physical scales are the fast adaptive composite grid method (FAC) [13] and the multi-level adaptive technique (MLAT) [14]. These procedures, currently being developed for application to advanced structural composites [15], could be adapted to MCM's in a fairly direct manner. The basic steps in a process which can combine theses techniques are:

1. Solve the problem over the global domain, Ω, using an appropriate solution procedure. A key operation involved in this process is the material averaging procedure. In a multiscale

adaptive analysis mathematical homogenization procedures are employed for this averaging since they provide an appropriate framework for evaluating local contributions to the error due to material averaging. A finite element discretization is constructed of the resulting strong form. The numerical solution to this global procedure is represented by

$$u_0 = A_0^{-1} f_0 \tag{1}$$

where u_0 is the solution to the field variable on the averaged global level, f_0 is the loading function on the global level, and A_0^{-1} is the represents the inverse of the global level stiffness matrix. A direct reduction process is typically applied to solve this system.

2. Select the critical region(s) for local analysis. Refer to a selected local region as Ω_L
3. Prolongate the global solution onto the interface between the global and local regions. The prolongation operator, Q_I, is constructed following the constructs used in homogenization theory [15]. In equation form

$$u_L|_{\Gamma_I} = Q_I u_0 \tag{2}$$

where u_L is the local solution variables and Γ_I is the interface boundary between the local and global domains.
4. The problem is solved on the local grid subjected to the local forces, f_L and the prescribed essential boundary conditions on the interface. The problem statement is solve

$$A_L u_L = f_L \tag{3}$$

subject to

$$u_L = u_L|_{\Gamma_I} \text{ on } \Gamma_I \tag{4}$$

where A_L is the local stiffness matrix. Equation 3 may be solved exactly [13] or approximately [14].
5. Calculate the composite grid residual

$$r_0 := Q^* r_L + r_G \tag{5}$$

where the contribution due the local solution process is

$$r_L = (f_L - A_L u_L)_{\overline{\Omega}_L} \tag{6}$$

which is operated on by the homogenization based restriction operator Q^* in the residual equation [15], and the contribution due the global solution process is

$$r_G = (f_0 - A_0 u_0)_{\Omega/\Omega_L} \tag{7}$$

It is important to note that even when equation 3 is solved exactly, there is still a local contribution due to equation 6 which represents the fluxes caused by the local solution along the interface boundary between the local and global domains, Γ_I. When equation 3 is solved approximately, there is also a contribution from over the local domain. Also note that the contribution form the global solution, equation 6, is also not identically zero since this contribution is defined only the global minus the local domain.

6. A global solution correction is constructed by

$$\Delta u_0 = w A_0^{-1} r_0 \tag{8}$$

where w is a global grid relaxation parameter.

7. The global solution is then updated as

$$u_0 := u_0 + \Delta u_0 \tag{9}$$

If the selected norm of Δu_0 is small enough, the solution is converged and the process is terminated. Otherwise, the interactions between the global and local solutions has not yet converged and the iterative process is continued by returning to step 3.

CLOSING REMARKS

A procedure has been presented to perform two scale heat conduction and thermomechanical analyses of multichip interconnects. The goal of solving the problem on two physical scales is to provide a means to obtain locally accurate solutions in critical regions using a computationally efficient technique. The procedures presented have been seamlessly integrated into a package which can perform these analyses automatically given a physical description of the interconnect.

As pointed out in the last section, the reliability of the numerical solution procedures can be improved by explicitly controlling the error introduced by a two scale analysis process. In addition, a number of other areas should receive consideration in the further development of these techniques. Some of these areas are:

1. A more complete examination of the accuracy of applying averaging procedures over entire interconnect layers in the presents of sizeable spatial non-uniformity in the distribution of the constituents.
2. More detailed consideration of the influence of the manufacturing process on the production of initial stress fields and formation of local geometric details.
3. Addition of procedures to automatically isolate critical local regions.
4. Addition of locally nonlinear failure analysis procedures to accurately predict the failure of specific connections.

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