MULTIPHYSICS MODELLING FOR ELECTRONICS DESIGN

John Parry
Flomerics Limited
Bridge Road, Hampton Court
Surrey, UK
Email: john.parry@flomerics.co.uk

Chris Bailey
Centre for Numerical Modelling and Process Analysis
University of Greenwich
Greenwich, London, UK.
Email: c.bailey@greenwich.ac.uk

Chris Aldham
Flomerics Limited
Bridge Road, Hampton Court
Surrey, UK
Email: chris.aldham@flomerics.co.uk

ABSTRACT

The future of many companies will depend to a large extent on their ability to initiate techniques that bring schedules, performance, tests, support, production, life-cycle-costs, reliability prediction and quality control into the earliest stages of the product creation process. Important questions for an engineer who is responsible for the quality of electronic parts such as printed circuit boards (PCBs) during design, production, assembly and after-sales support are: What is the impact of temperature? What is the impact of this temperature on the stress produced in the components? What is the electromagnetic compatibility (EMC) associated with such a design?

At present, thermal, stress and EMC calculations are undertaken using different software tools that each require model build and meshing. This leads to a large investment in time, and hence cost, to undertake each of these simulations. This paper discusses the progression towards a fully integrated software environment, based on a common data model and user interface, having the capability to predict temperature, stress and EMC fields in a coupled manner. Such a modelling environment used early within the design stage of an electronic product will provide engineers with fast solutions to questions regarding thermal, stress and EMC issues. The paper concentrates on recent developments in creating such an integrated modeling environment with preliminary results from the analyses conducted. Further research into the thermal and stress related aspects of the paper is being conducted under a nationally funded project, while their application in reliability prediction will be addressed in a new European project called PROFIT.

INTRODUCTION

Increasing global competition is a significant factor impacting the design of modern electronic products. While the product development time for electronic systems in the early 1980s was often years, portable computing and consumer products for example have today a time-to-market of only a few months. These rapid times-to-market do not leave room for time-consuming trial and error approaches that have been the normal practice in the past. Today, experimentally validated computational modeling has become the preferred choice for rapidly carrying out numerous 'what-if' studies during design. At present such modelling technologies do not, in general, provide coupled solutions for thermal, mechanical and EMC issues. For example at the systems level an engineer may be interested in predicting the flow and temperature fields throughout the system, and then to immediately use these results to calculate the stress fields within a circuit board assembly or a chip component due to the thermal miss-match between different materials. The need for such an integrated modeling approach is emphasised in the Semiconductor Industry Association's 1997 Roadmap document [1], which states:

> *"Developments in chip size, packaging techniques, power dissipation, and switching speed require new simulation tools that treat thermal, mechanical and electrical effects self-consistently."*

This roadmap focuses primarily on issues associated with semiconductor manufacture and packaging. However, the need for a self-consistent solution of thermal, mechanical and electromagnetic effects extends from the package level up to system level.

At package level, thermal derating is being replaced by uprating [2], increasing the temperature at which packages operate and hence the temperature range of a power-on / power-off cycle. Future electronics will heavily depend on successful chip packaging. Increasing chip sizes cause larger in-plane temperature gradients leading to possible performance problems, and, more severely, to larger thermally-induced stresses within the die and die attach.

At board-level, increasing package sizes increase the relative in-plane displacements between the package and the board and hence the strains on the package-board interconnection. Increasing copper content of the board increases package-package thermal interaction, and package-mounted heat sinks reduce the convective cooling of the components in their wake. If the heat sink is ungrounded, common-mode RF coupling occurs between the die and heat sink, which becomes an antenna radiating clock harmonics throughout the frequency spectrum.

At the system-level, the cooling of packaged electronics is heavily influenced by the restrictions imposed by the potential shielding necessary to suppress electromagnetic emissions. Enclosing the electronics in sealed metal cases provides good shielding but obviously restricts air movement necessary for adequate cooling. In many cases the suppression of emissions is directly in conflict with the cooling needs. At present engineers have to rely on their experience and judgement (and a test and then correct procedure) to pass the EMC certification hurdle, which is far from ideal. The influence of both thermal and mechanical effects on equipment reliability is now widely recognized, and physics-of-failure based approaches to the design, production and reliability assessment of electronics equipment are being adopted [3,4].

To be successful, the design of today's electronic systems requires the adoption of a multi-disciplinary approach early within the design process; involving electrical, thermal, mechanical, and packaging engineers to make the necessary design trade offs.

To avoid discovering many problems late in the design process, design evaluations have to be made throughout the design process using simulation tools that provide fast coupled solutions for thermal, mechanical and EMC fields.

TOWARDS A MULTIPHYSICS MODELLING APPROACH.

Computational mechanics technology is now used extensively in a wide range of industrial sectors including electronics, aerospace, automobile, medical, etc. Historically this technology has evolved along a number of distinct paths – for example Computational Fluid Dynamics (CFD), Computational Solid Mechanics (CSM), and Computational Electromagnetics (CEM). In the past, if the process to be modelled was fluids-based then the modelling technology used would be based on developed CFD techniques generally using Finite Volume discretization methods. If the process was solids-based then the CSM techniques used would be based on Finite Element methods. This evolution of computational mechanics technology has, in general, inhibited the modelling of phenomena that can be termed 'multi-physics' where for example solids and fluids interact. Over the last five years a large amount effort has been given to develop algorithms and associated software tools that are capable of representing and simulating such processes [5,6]. This has been evident in the development of simulation tools for solidification processes associated with the casting of metal components for the aerospace industry [7].

Flomerics is developing novel technologies that will provide a unified modelling framework for thermal, mechanical, and electromagnetic predictions. This multi-physics methodology is based on numerical algorithms that use current best-in-class techniques that are integrated in an efficient and robust manner. Figure 1 illustrates the relationship between the existing FLOTHERM product, and those under development - FLO/STRESS and FLO/EMC, which will respectively provide predictions of stress and electromagnetic fields associated with electronic systems.

The tight integration between FLOTHERM and both FLO/STRESS and FLO/EMC will provide users with a common user interface that facilitates the ease of model building and the interpretation of the results. Eventually the system will use a common data model for storage of all geometrical and simulation data allowing a single model to be analysed in many ways.

The system will require sophisticated algorithms to enable it to correctly interpret the input for the various solver modules. For example, a fan in FLOTHERM is an air moving device,

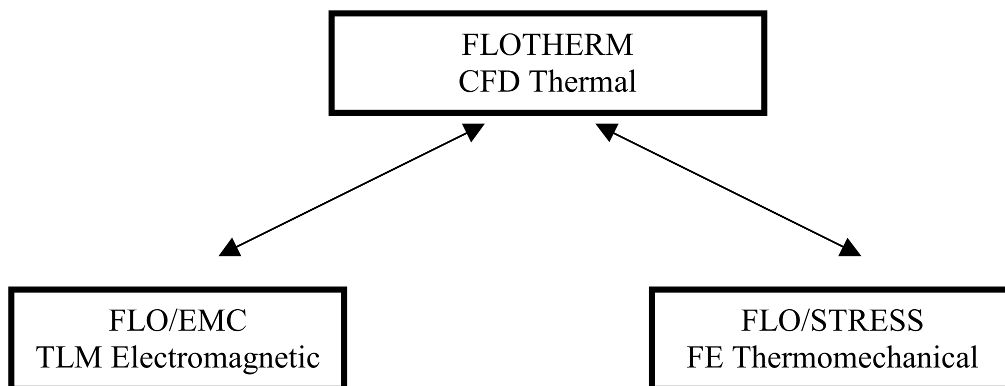

Fig. 1: Multi-Disciplinary Modelling Environment

it blows air around the system. In FLO/EMC this air movement is not important and the fan will appear just as an opening (particularly when it has plastic blades) with a hub in the middle. Understanding the mapping of objects between the analysis types is one of the big challenges for the development of a common data model.

FLO/EMC

FLO/EMC uses a Transmission-Line Modelling Method (TLM) approach to solve Maxwell's equations for electric and magnetic fields [8]. The approach is based on a Cartesian mesh similar to that used in FLOTHERM. The method is time domain based and so provides a broadband solution (i.e. covering a wide frequency range) from a single run. Unlike most thermal analyses where small details are often unimportant, small details are normally critical for electromagnetic emissions. The small cracks that are formed when two surfaces meet must be accurately represented if realistic results are to be obtained from simulations.

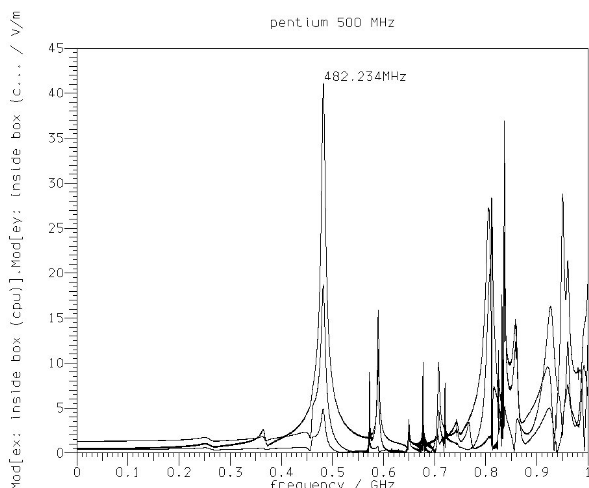

Fig. 2. Frequency response in centre of PC system

This requires are very efficient solver (both in memory and CPU-time) if useful simulations are to be obtained. At this point it is useful to say something about the quality of results currently obtainable from electromagnetic simulations. Apart from the very simplest systems it is not possible to simulate in detail a system and expect to obtain exactly the same data as would be measured in an anechoic chamber. There are simply too many electromagnetic sources, potential sources and influences for them all to be considered in detail in the computer models. However, careful consideration of the system to be studied will allow designers to identify trends such as trouble spots, possible weakness and likely solutions. Like so many simulation methods the analysis provides insights into the design, not design solutions. Designers must understand what they are doing and why.

Illustrative Example

As an example, consider the simulation of a typical PC system. The most important features are included in the model, especially the gasket filled slots (where the removable side of the case meets the rest of the casing). A simple 1V/m source is excited under the heat sink to represent a signal from the processor.

Figure 2 shows the frequency response measured in the centre of the system.

The resonance at 482MHz is clearly visible and the broad base of this peak indicates that a 500MHz processor is likely to excite this resonance. Special measures are necessary to avoid emissions coming out of the system.

The surface currents at 482 MHz are shown in Figure 3.

The high current visible on most surfaces is a result of the resonance. Also clear is the current around the two side slots that will lead to emissions outside the system.

The radiation pattern shown in figure 4 clearly shows the

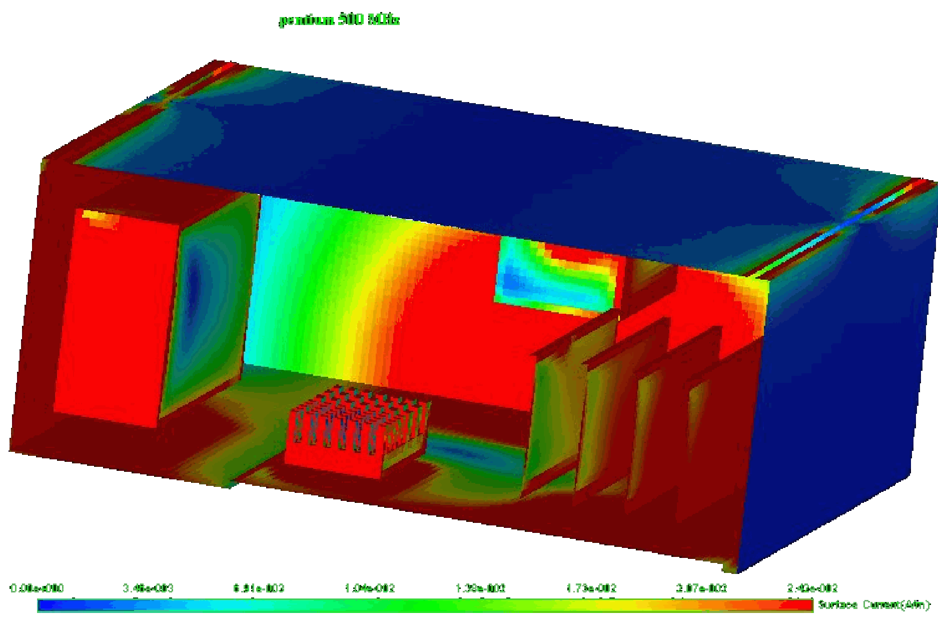

Fig. 3. Surface currents at 482MHz

radiation coming from the two slots as large lobes in the plot.

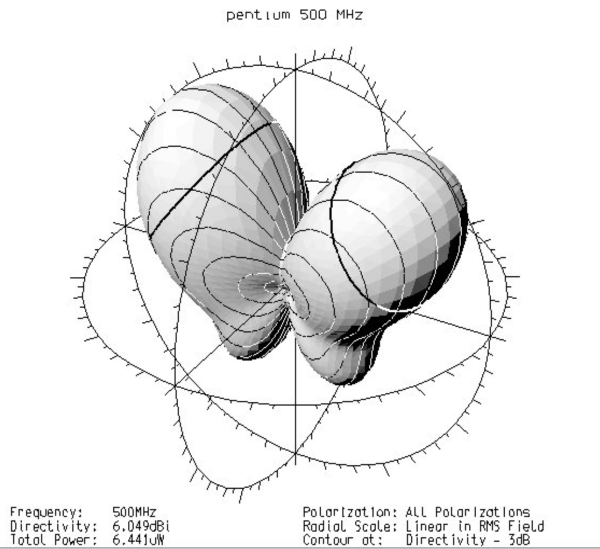

Fig. 4. Radiation pattern from PC system

FLO/STRESS

The current FLOTHERM – FLO/STRESS interface uses the FLOTHERM model where only the mesh in the solid regions of interest is used within the stress calculation. Figure 5 summarises the input data and results generated by FLOTHERM and FLO/STRESS. Geometry, grid and temperature information is passed from FLOTHERM to FLO/STRESS during a simulation.

The stress equations solved in FLO/STRESS are discretized using traditional finite element type procedures, where the change in temperature predicted by FLOTHERM is used to calculate the solid deformation for a board or chip component. These calculations are only undertaken using a subset of the FLOTHERM mesh representing the region of interest to the design engineer.

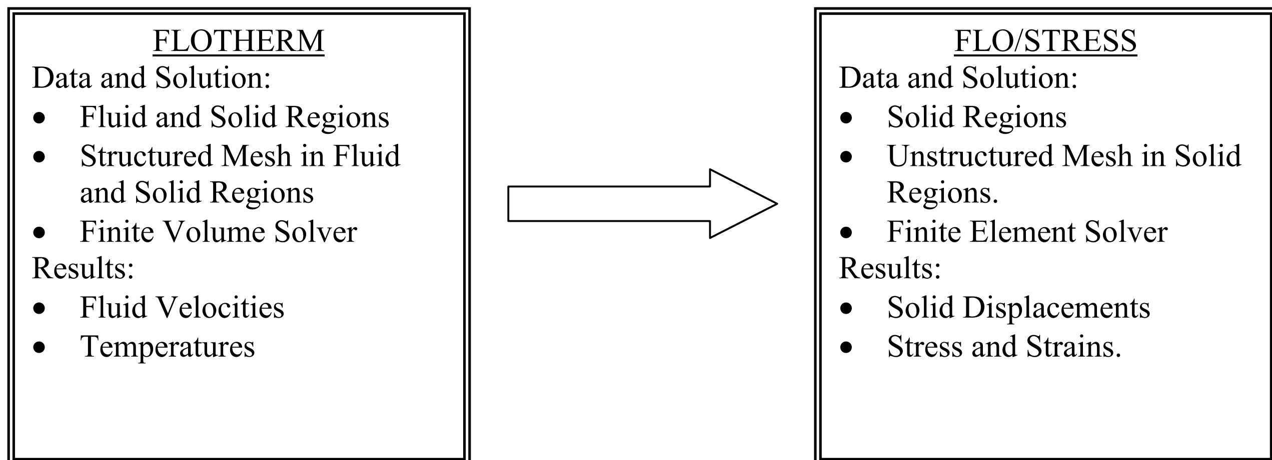

Fig. 5: Integration between FLOTHERM and FLO/STRESS

Although the mesh used within the FLO/STRESS calculation is unstructured it is built up from the FLOTHERM mesh used for that particular component. The transfer of data from FLOTHERM to FLO/STRESS during a simulation appears seamless, as the FLO/STRESS model is a subset of the FLOTHERM model and no extra model build or meshing is required. The only extra input required from a current FLOTHERM user will be relevant materials data and boundary conditions required for the stress calculation. At the outset of the development of FLO/STRESS care has been taken to ensure that very little extra work will be required by current FLOTHERM users to use predicted temperatures for a fast stress calculation. This approach will provide current users the capability to undertake a fast stress calculation based on predicted FLOTHERM thermal gradients.

Illustrative Example

The example chosen is the Motorola PowerPC™ 604 C4/CBGA on a 2-inch test coupon in a computational wind tunnel. The C4 interconnection provides both the electrical and the mechanical connections for the die to the ceramic substrate. After the C4 solder bumps are reflowed, epoxy (encapsulant) is under-filled between the die and the substrate. Under-fill material is commonly used on large high-power die, although this is not a requirement of the C4 technology. The package substrate is a 21mm multi-layer co-fired ceramic. The package-to-board interconnection is by an array of orthogonal 90/10 (lead/tin) solder balls on a 1.27mm pitch.

The detailed model of the package was constructed in FLOTHERM, which then solved the steady-state conjugate heat transfer present in the wind tunnel calculation. The package was constructed from conducting cuboid blocks representing the die, C4/underfill, co-fired ceramic substrate, and the ball array. During assembly of the C4/CBGA package to the board, the higher melting point (90/10) solder balls do not collapse [9] but are soldered to the board, as they are to the package, with lower melting point (63/37) solder. To a first approximation, the 90/10 solder ball is encased

within a cylinder of 63/37 solder. In the model, the joint is cuboidal, having the same cross-sectional area and height as the cylinder. The volume of the 90/10 and 63/37 solder are also preserved, with the 63/37 solder being distributed equally above and below the 90/10 solder. One element is used for each of these layers although more can be used if required. This approach is similar to the global-local modelling techniques used to simulate the thermal stress at the package and solder bump levels [10]. In the case analysed here we are predicting the stresses at the package (Global) level. A schematic giving a cross-section through the model of the package is shown in the figure 6.

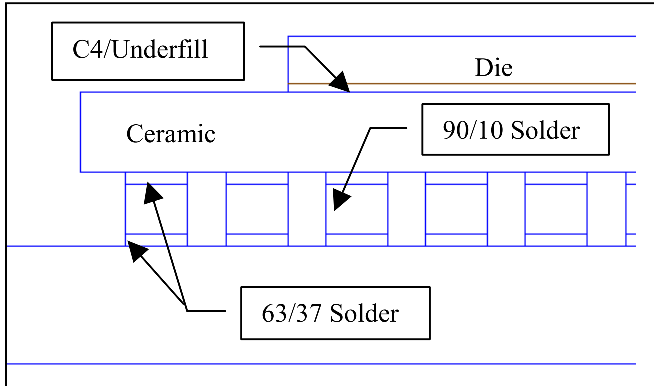

Fig. 6: Schematic of C4/CBGA and PCB

The properties of the materials used in the model are given in Table 1.

Material	Thermal Conductivity (W/mK)	CTE (ppm)	Young's Modulus (Pa)	Poisson's Ratio (-)
PCB	5.0	15.0	18.2E9	0.25
Sn90/Pb10	35.5	27.8	24.0E9	0.4
Sn63/Pb37	50.6	25.2	44.4E9	0.36
Ceramic	16.5	6.7	300.0E9	0.23
C4/U'fill	0.8	52.0	1.0E9	0.3
Silicon	120	2.3	162.0E9	0.28

Table 1: Material Properties Used In Model

For the PCB, the thermomechanical properties used are those for FR4, whereas the thermal conductivity is that for a board containing approximately ½Oz copper. The effective (through plane) thermal conductivity used for the C4/Underfill was calculated from data on the size and number of the C4 bumps and the thermal conductivities of the solder and the underfill epoxy [11]. In this illustrative work the thermomechanical properties used for the C4/Underfill are those for the underfill epoxy.

After performing the thermal calculation in the usual way, the thermally-induced stresses were solved using a prototype thermomechanical stress module, FLO/STRESS, built into FLOTHERM. In the calculation reported here, the stress solver used 8-node brick elements to replicate the mesh in the solid used by the thermal design tool. However, this is not a limitation as the stress solver uses unstructured mesh technology and can have a refined mesh in this area if so desired. In order to perform the stress calculation an assembly in the model is targeted, to which constraints are applied, and a stress-free temperature defined for each object. The stress-free temperature for all objects was assumed to be 170˚C in this analysis, being the cure temperature for the underfill. The computational overhead required is given in table 2. In this particular example, the stress analysis requires less computational time than that for the thermal analysis. The primary reason for this is that the mesh is much smaller, since displacements are only calculated in the solid regions of the target assembly within the model.

	Thermal Model	Thermomechanical Model
Number of cells/ elements	83328	14552
Relative solution Time	1.0	0.57

Table 2: Model Characteristics

Once the model has been solved, the results can be post-processed in the usual way. A selection of the results obtained is presented below.

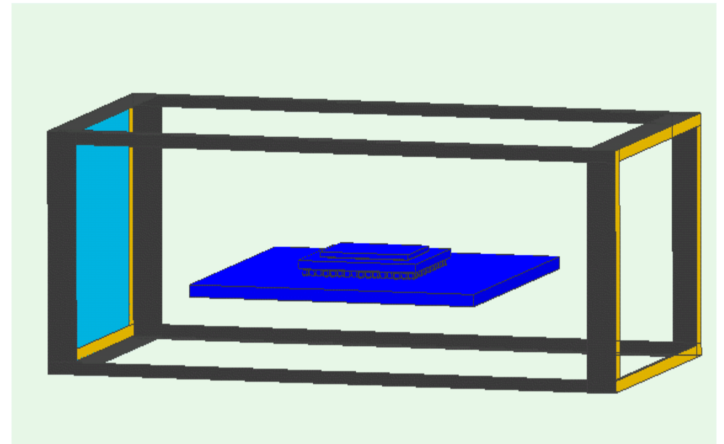

Fig. 7: Schematic of Board Assembly in Wind Tunnel.

The results can be seen to be qualitatively correct. Figure 8 shows the temperature profile through the assembly where the effect of the wind tunnel in cooling the assembly can be clearly be seen, as flow passes from left to right in the plot. The temperature changes occurring will result in deformation of the assembly and hence stress due to the thermal mismatch in materials. In this case the thermal mismatch between the substrate and the solder joints is greater than the thermal mismatch between the solder joints and the PCB. This results in high von-mises stress values at the solder-substrate interface region seen in figure 9.

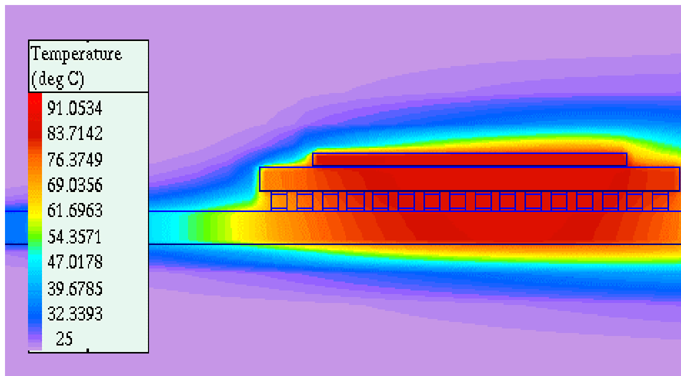

Fig. 8: Temperatures On Package and Board Centerline.

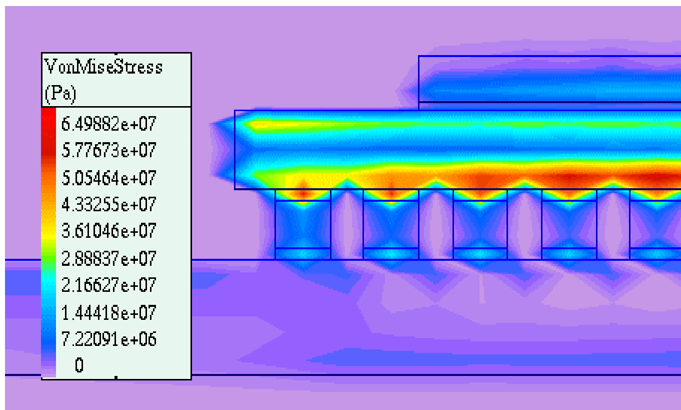

Fig. 9: Von Mises Stress in Solder Joints Adjacent To Package and Board Centerline.

The representation of the solder bumps is made using a continuum mesh approach. Although we have currently used a fairly course mesh based on brick elements, this is in no way a limitation, as FLO/STRESS uses an unstructured solver where further mesh refinement can be made. Figure 10 shows the stress magnitudes at the solder-package interface where again we can see a high magnitude of stress. Prediction of the highest stresses in the solder joints adjacent to the package substrate is expected. An investigation into the behavior of CBGA 625 package during temperature cycling revealed that when the package was subjected to rapid thermal cycling from -55°C to 125°C failures mainly occurred at the package-solder joint interface, being driven by local stress conditions [12].

Figure 11 shows the stress magnitude along the die attach region. Clearly we can see a lower stress magnitude in this region as compared to the solder-package interface. This C4/underfill region is helping to relieve stress in the die due to its relatively low Young's Modulus.

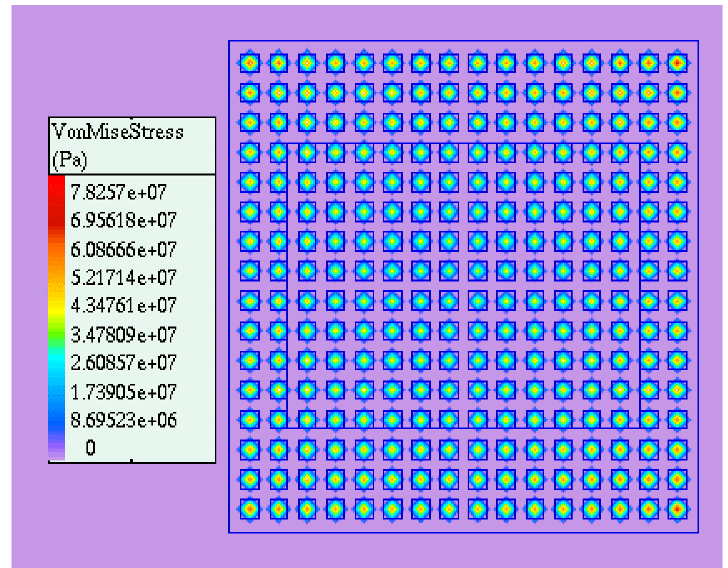

Fig. 10: Von Mises Stress in Solder Joints Adjacent to Package.

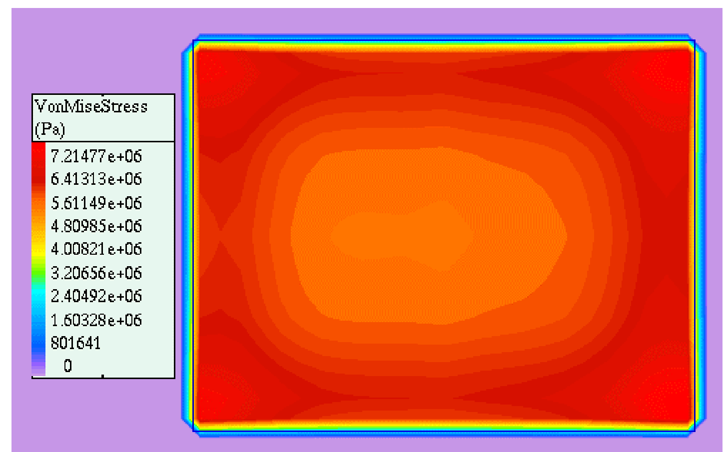

Fig. 11: Von Mises Stress in Die Attach.

CONCLUSIONS

Flomerics is actively developing new software tools that will build upon the FLOTHERM thermal analysis tool to provide predictions for thermally-induced stresses within, and EMC fields around electronic systems. This paper discusses recent developments in multiphysics analysis for electronics design, covering the thermal, thermomechanical and EMC analysis domains. Some early results are presented for both the thermomechanical and EMC tools (FLO/STRESS and FLO/EMC).

The example EMC analysis shows that it is possible to perform EMC simulations on geometries similar to those used in thermal models. Although many details are omitted in the model important features like narrow slots can be considered. The main resonant frequencies can be identified and the designers can then take action to avoid these causing

problems (by changing geometry to move the resonance or avoiding sources likely to excite the resonance). Using the knowledge gained at an early stage in the design process can dramatically improve the likelihood of the system passing the appropriate tests and achieving certification.

The example thermomechanical analysis has demonstrated the current capability for the analysis of a package on a test board. This simple application, based on a system-level temperature field, has been used to illustrate the concept of reusing the thermal model to perform a first-order accurate thermomechanical analysis. Such a board-level analysis could be used to investigate solder joint reliability. One main advantage of a combined system-level thermal and thermomechanical tool is that the thermal environment of the board during operation can be accurately predicted, making it possible to simulate the functional cycling of a whole board, by considering only the critical components in detail. Other components could be represented more crudely to include their thermal effect on the board, but excluded from the mechanical calculation. Another potential application is in the prediction of the likely board warpage during reflow. At the package-level, package designers could use this approach to simultaneously investigate the thermal and thermomechanical behavior of a new design variation, for example to check the reliability of a lead frame or paddle design, or to assess die attach reliability. At the system-level the approach can be used to investigate the mechanical loading on board mountings, the effect of solar loading on plastic enclosures, etc.

FUTURE CHALLENGES

There are many challenges left in the search for an optimum thermal, thermomechanical and EMC solution. Ensuring that all objects in the model are correctly interpreted by the thermal, stress and EM solvers sounds obvious but in practice is very difficult to carry out. In most cases it comes down to a fundamental understanding of which features have to be modelled and in how much detail.

For EMC simulation the PCB and the components on it represent a great challenge. Virtually every component and every trace on the PCB is a potential source of electromagnetic radiation and an influence on the radiation. Of course the goal of the work must be remembered here. The object is not to create an analysis system that will perform "perfect" calculations, but rather to allow designers to make informed design decisions about the equipment they are constructing. Often these decisions have to be made before all detailed information is available. Understanding how to use what information is available at different stages in the design process is vital. Combining EMC, thermal and thermomechanical analysis provides an opportunity to shorten design times.

Using a more accurate representation of the thermal environment in the thermomechanical analysis may also lead to more accurate the stress data for use in reliability predictions, but requires further research. Research in this subject has recently commenced through a 3-year European Community funded project, PROFIT (IST-1999-12529) which started in January 2000.

PROFIT aims to create methods and tools to enable rapid assessment of thermal parameters affecting yield, performance, reliability and safety in electronic equipment. However, analysis is seriously hampered by the lack of standard methods to predict temperature gradients in time and space, with sufficient accuracy. The PROFIT project aims to overcome these drawbacks through major improvements in experimental techniques to acquire better input data for thermal modelling via non-linear parameter estimation methods, and improved transient thermal characterisation of components. Standardisation is considered an important deliverable. Ultimately, the results of PROFIT will be suited for implementation in emerging virtual prototyping methods and physics-based reliability analysis software.

The industrial challenges and solutions offered by PROFIT are:

- Cost/weight reduction with better quality, via significant improvements in temperature prediction for virtual prototyping
- Physics-based prediction of reliability, via accurate prediction of temperature gradients in time and space
- Yield improvement of packages, via better-defined rejection criteria based on in-line quality testing
- Awareness of problems due to the absence of useful design specs, via dissemination of combined thermal expertise in Europe
- Standardisation of thermal characterisation, via European focal point to support international efforts.

The PROFIT project is co-ordinated by Philips Research. The project consortium includes semiconductor manufacturers (Philips Semiconductors, Infineon Technologies, ST Microelectronics); system makers (Nokia, Philips); thermal analysis software vendors (Flomerics, MicRed); a statistics expert centre (Centre for Quantitative Methods); a university specializing in electrothermal analysis and transient measurements (Technical University of Budapest); and a major research institution contributing in the fabrication of test dies and tool integration (TIMA).

The work programme will focus on major improvements in thermal analysis throughout the design chain, from device via package and board to system. Novel test set-ups will be built in order to measure important parameters required for accurate numerical analysis, such as interface resistances, emissivities, local boundary conditions and local board thermal conductivities. Transient measurements at device and package level will be performed to assess data quality. Analysis of the data will be treated with novel, non-linear parameter estimation methods. Software will be improved, developed and integrated to facilitate the application of the project results in performance and reliability calculations.

Various demonstrators showing the final deliverables are foreseen. The steady-state thermal characterisation of compact models will be extended to the transient domain. Yearly workshops will be organised to promote discussion amongst experts, and to facilitate early standardisation. In short, the innovative elements of the project are:

- Novel statistical approach for the optimisation of experiments, analysis of transient data and generation of dynamic compact models.
- Novel measurement techniques for the acquisition of input data.
- Novel electrothermal and thermomechanical board/system level software.
- New proposals for the standardisation of transient thermal characterisation.

During PROFIT, Flomerics will research into compact thermomechanical representations of thin and composite structures commonly found in electronics assemblies. The end user partners, Nokia and Philips, will compare the results of using data obtained from FLO/STRESS with existing in-house reliability prediction protocols. Developments to the FLO/STRESS prototype are being undertaken through a second 2-year technology transfer project with Greenwich University (TCS Programme Grant # 2976).

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