Application of thermo-mechanical numerical prototyping in electronic packaging

A. Wymysłowski

Wrocław University of Technology, Faculty of Microsystem Electronics and Photonics, ul. Janiszewskiego11/17, 50-372 Wrocław, Poland

ABSTRACT: Nowadays in most of the leading electronic companies it is a common practise to use numerical prototyping methods and tools. The reason for that is on one hand short-time-to-market, enhanced functionality and improved quality but on the second hand the higher profitability of the electronic industry. Actually, in order to achieve the above goals it is required to master advanced thermo-mechanical modelling methods as well as experimental material characterization techniques. Especially, in electronic packaging thermo-mechanical aspects are playing a dominant role as they are influencing more and more the reliability of final electronic systems.

1. Introduction

Electronic packaging refers to the packaging of integrated circuits (IC), chips (dies), their mounting and interconnecting on PCB's for signal and power transmission and heat dissipation. In electronic systems, packaging materials may also serve as electrical conductors or insulators, provide structure, thermal paths and protect the circuits from environmental factors such as moisture, contamination, hostile chemicals and radiation. Electronic packaging can be divided into four levels of which level first and second seem to be the most important. Level first refers to chip and system packaging while level second refers to mounting and interconnecting packaged and/or bare chips on PCB surface [1]. The typical structure at first and second packaging level is shown in the figure 1 [2].

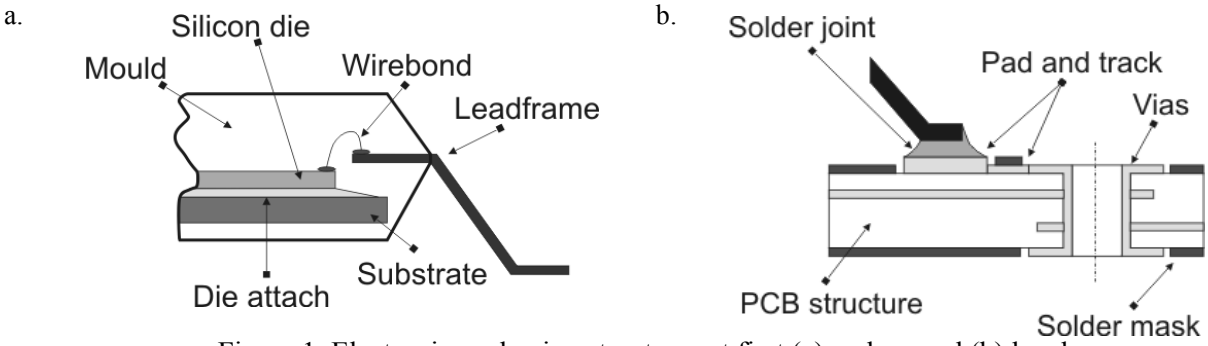
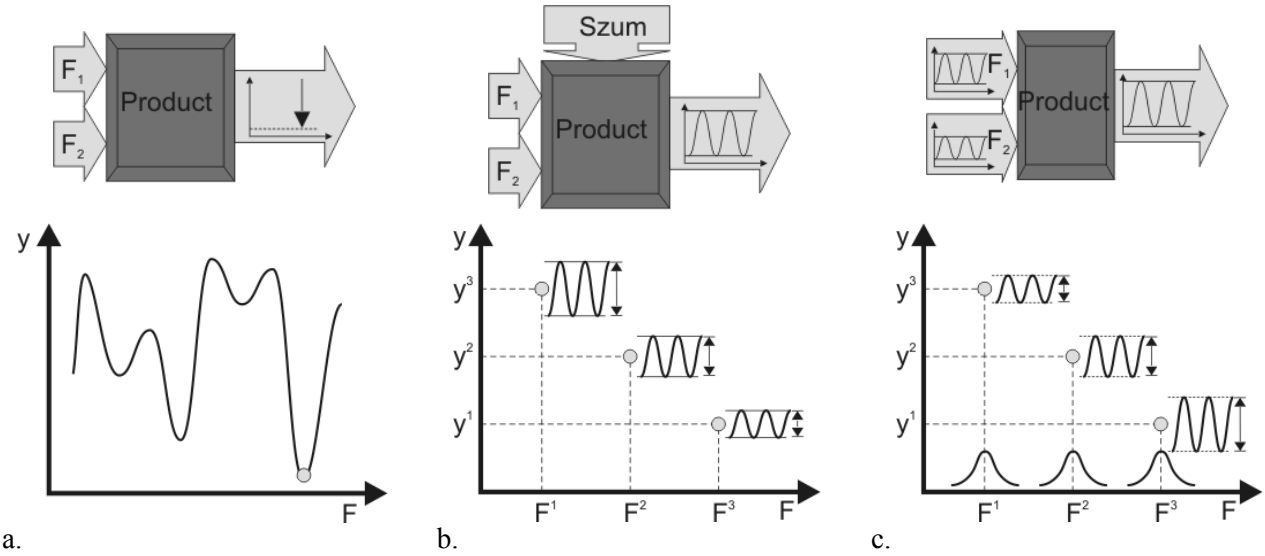


Figure 1. Electronic packaging structures at first (a) and second (b) level.

The current technology trend in electronic packaging is rapid development, which can be enhanced by numerical thermo-mechanical prototyping. But the key problem is reliable knowledge on materials, interfaces, physical phenomena and probable failure mechanisms. The ongoing trend towards higher reliability and better thermo-mechanical performance of components and modules requires on one hand interdisciplinary knowledge and on the second hand the advanced thermo-mechanical prototyping methods.

On the other hand numerical prototyping does not only refer to the problem of numerical simulations. The final goal is to achieve the product that would fulfill high quality specifications and low cost requirements. Therefore, process of numerical prototyping can be divided into three stages: optimization, sensitivity analysis and tolerance design. The goal of the optimization is to find out the most suitable solution depending on the given constraints, the sensitivity analysis is to minimize the influence of noise and/or uncontrollable factors on the product output while the tolerance design is to define the

acceptable tolerances of controllable factors in order to minimize the random scatter of the product output. The graphical representation of the numerical prototyping stages is given in Figure 2 [2]



a. b. c.

Figure 2. Numerical prototyping stages: optimization (a), sensitivity analysis (b) and tolerance design (c) [2].

2. Selected problems of thermo-mechanical numerical prototyping in electronic packaging

In order to address properly reliability of electronic packaging numerical modelling methods are to be combined with numerical prototyping techniques. Actually, the new trend is to move numerical prototyping into the direction where designs are additionally tested according to the so-called numerical qualification. Nevertheless, in order to achieve that goal there is a need for using advanced numerical modelling techniques along with validation methods, e.g. based on dedicated experiments. There is a direct relation between proper material characterization and results of numerical prototyping. Improved reliability of electronic systems can be achieved as long as there are properly addressed such problems as adequate failure modes and criteria. Then they should be transferred into adequate modelling methods including multi-dimensional, multi-physics, multi-loading and complex material behaviour description. Nevertheless, it requires development of advanced and sophisticated experimental material characterization methods and application of advanced numerical procedures. For example, one of the current numerical prototyping trends is addressed towards complex numerical analysis of failures including delamination, cracking, fatigue, moisture absorption, etc. It is worthy mentioning that some of the above failure modes require multi-scale and multi-physics phenomena analysis, which can be properly addressed only by introducing continuous and discrete modeling techniques based on finite element and molecular modeling correspondingly [3].

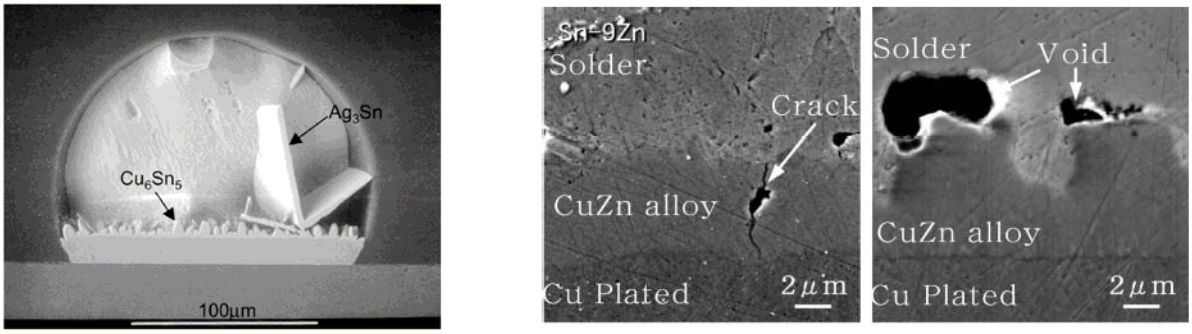
2.1. Multi-physics problems

Multi-physics numerical analysis is required in order to address properly such problems as failure modes and criteria, which require both theoretical analysis and experimental characterization. On the other hand this can not be fulfilled without complex material behaviour, which require adequate modelling techniques and sophisticated material characterization, as in case of viscoelasticity. Thus, such problems as adequate complex material structures, problem of thin layers and material interface characterization are to be addressed properly [4,5].

2.1.1. MATERIAL STRUCTURES

In the area of numerical simulations the availability of accurate thermo-mechanical material data as the input for simulations is the most essential. In electronic packaging this refers especially to such materials as solders, encapsulates, adhesives, which express complex material behavior. The complex behavior means that the results of experimental tests are very much dependent on testing conditions as well as design and manufacture of test specimens. Furthermore, literature data shows substantial variation in measured values of mechanical properties, even for such well known materials as solder alloys. Variations in literature data may be attributed to the fact that materials due to external loads (e.g. temperature) behave differently. Most of the materials can be classified according to the following groups: linear or nonlinear, isothermal or temperature dependent, homogenous or non-homogenous, isotropic or anisotropic. New technologies demand new materials. Polymer

composites, with their wide range of possible fillers and polymers, open the way to an enormous range of materials with differing chemical, physical, and mechanical properties. The ultimate goal of polymer composite research is to formulate procedures that will lead to the design of composites with preset, i.e. specified, properties. Continuing reduction in dimensions of electronic packaging requires better knowledge of materials. e.g. stochastic behavior, interactions between different materials and introducing new phenomena, which are relevant to micro and nano scale. The interaction between different materials, typically in joints and components may also influence the material properties due to the existence of intermetallic compounds, which can accelerate fatigue failure. Thus, the micro structure of solders is one of the great concerns, as given in Figure 3 [5].

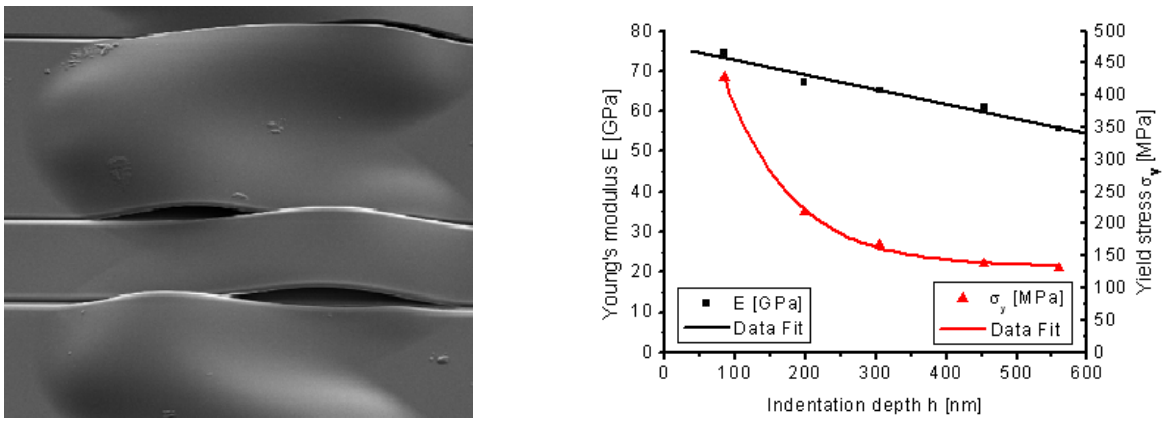


a. b.

Figure 3. Problem of intermetallic layer (a) and material composites in microelectronic packaging (b) [5]

2.1.2. THIN LAYERS

Miniaturization of many types or microelectronic devices is done mainly due to the ongoing progress in fabrication, which leads for example to the problem of thin films. Residual stress in thin films induced during fabrication processes play an important role in the mechanical behavior of microelectronic devices. These stresses may mechanically damage the device through cracking or delamination. It is acknowledged that device reliability is strongly related to the level of residual stress in the component films. The properties of thin films are often significantly different from those of bulk materials because they may depend not only on the material but also on the film thickness, microstructure, substrate, technological processes, etc. There are already many techniques for thin film characterization, but no standard techniques currently exist, as do for example for bulk materials. One of them is method referred as nanoindentation technique, which allows for assessment of mechanical properties, as shown in the figure 4 [5,6].



a. b.

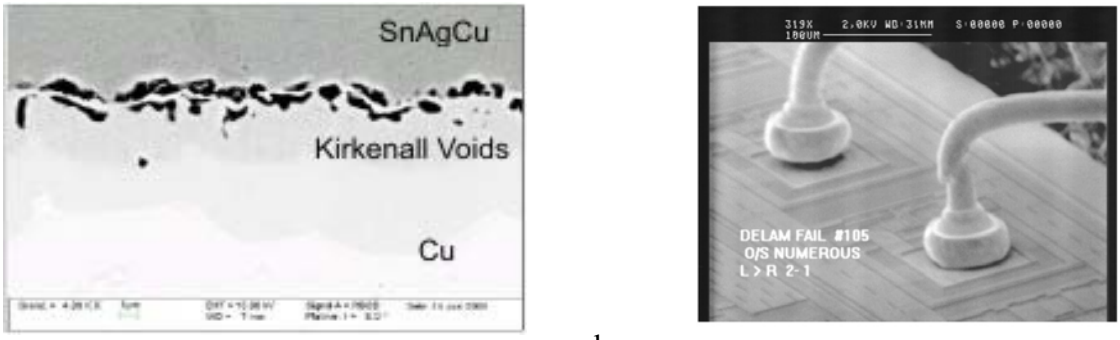
Figure 4. Problem of thin films delamination and material data of elasto-plastic model for different nanoindentation depths of thin Al layer [5,6].

Additionally due to the ongoing miniaturization the component sizes often approach the characteristic length of individual grains. With components comprised of only a few grains there is not enough random orientation of a significant number of grains to derive reliable material properties. This is an area that could be addressed by molecular modeling techniques. Thin films deposited on substrates are subjected to a variety of internal stresses and external applied forces, which are likely to damage the device. The stability of the deposited films is another factor determining their reliability. In addition reliability models for these devices should also

include features described by random distributions (variations in geometry, loading, defect distribution, material contamination etc.), which may require stochastic models. Another problem is due to the smoothness of the surfaces where large adhesion forces between fabricated structure components and substrates are encountered [5].

2.1.3. MATERIAL INTERFACE

Interface engineering is an increasingly important in order to improve all kinds of material interfaces as metals, ceramics, polymers, etc. Miniaturization results in interfaces becoming one of the dominant defects in electronic packaging. In some cases, interfaces are necessary to obtain specific phenomena. Thus problem of interfaces is a vital component of future technologies, which can be enhanced by molecular modeling techniques. The goal of interface engineering is to facilitate the properties of materials interfaces on the basis of a comprehensive understanding of the atomic structure of interfaces and their influence on interface structure properties. Unfortunately, establishing such a complete understanding is a huge task and requires interdisciplinary knowledge on the governing phenomena.



a. b.

Figure 5. Problem of material interface (a) and bond wire delamination in microelectronic packaging [6].

Bimaterial structures are commonly encountered in a variety of electronic packaging and lead to such failures as interface delamination. Interface properties are meant to have properties intermediate between those of the constituent materials. Thus, the mechanical behavior of the biomaterial structure and its performance is defined by the bulk properties of the materials but by the interface characteristics. In fact in case of a structure consisting of two edge-bonded elastic wedges of different materials, a stress-singularity is present at the vertex of the bimaterial interface. The power of this stress-singularity depends both on the bimaterial properties mismatch and on the wedge geometry. From the practical point of view, the existence of such a stress-singularity may lead to initiation of the failure processes due to e.g. initial defects at the interfaces, and lead to biomaterial delamination, as shown in Figure 6. Furthermore, an additional complexity arising in many interface problems is provided by significant residual and/or thermo-mechanical stresses present in the region close to the interface. The residual stress field is due to the bonding process and it is caused by the different CTE coefficients of the two constituent materials and by the elastic mismatch. On the other hand, many engineering components experience thermal loads and lead to stresses, which can cause as the result delamination of the bimaterial interface [5].

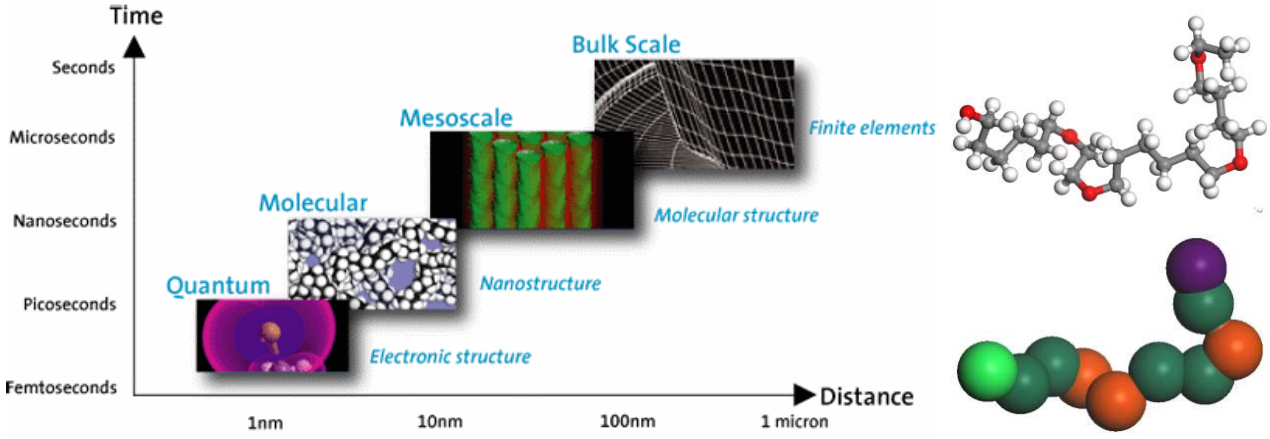
2.2. Multi-scale modelling

Numerical modeling techniques can be divided according to the relevant time and length scale domain, as given in Figure 6a. [7]. Depending on the scale modeling is referenced either as discrete or continuous. Molecular modeling is based on discrete analysis and takes into account such phenomena as: quantum mechanics, Van der Waals energy, Coulomb energy etc. Molecular modeling seems to have a number of benefits in reference to electronic packaging of which the most important ones are: field gradient problem, second order phenomena, multi-physics, stochastic behavior, discrete description. One of the contemporary research priorities is development multi-scale modeling techniques in different simulation methods and length/time-scales, which can play an increasingly important role in material design and understanding of both basic and complex material structures. Trial-and-error experimental approaches are inefficient ways of designing and discovering materials. Modeling of synthesis and processing is a powerful tool for deciding which directions to pursue, and which are non-feasible or uneconomic.

The ability of numerical simulation and optimization of electronic packaging materials and structures seems to be a basic requirement of the contemporary research activities. Unfortunately, in order to perform accurate and precise numerical simulations, it is required to cope with the interdisciplinary knowledge on the

multi-scale level and especially in case of the so-called meso-scale analysis, as shown in the Figure 6b. There are a couple of problems of electronic packaging that could be addressed by multi-scale modeling techniques [6]:

- thin films, which become a major research area in case of electronic packaging due to downscaling trend, protection coatings, etc.
- interfacial phenomena are essential to improve reliability of biomaterial structures, understand the properties of multifunctional materials, etc.
- development of new composites of materials of superior performance requires new instruments in order to characterize the structure and properties (mechanical, thermal, chemical, physical, etc.).



a. b.

Figure 6. Time and length scale problem in numerical modeling (a) and model transformation from molecular level to meso-scale level (b) [7].

2.3. Global and multi-objective optimization

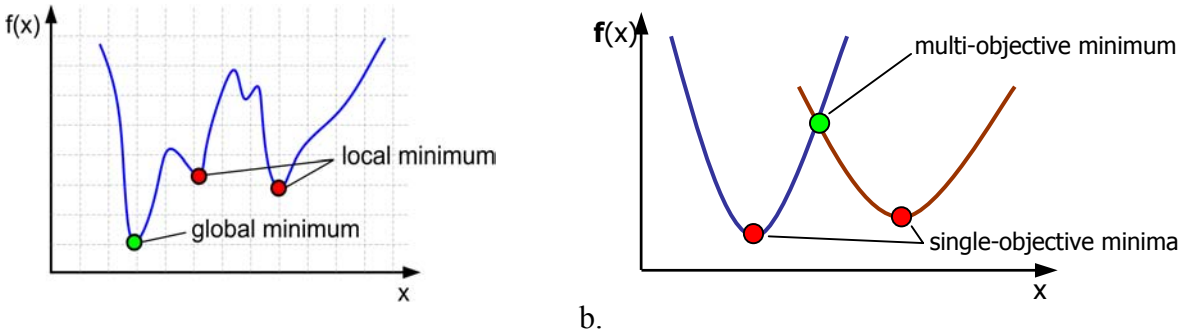
The problem of the packaging optimization seems to be one of the most important challenges in the area of numerical prototyping in electronic packaging. Optimization is in fact a separate branch of knowledge which focuses on development an application of different algorithms in order to find out an optimal solution due to a selected criteria and defined constraints. One of the crucial aspects of optimization is a vast number of optimization algorithms which are classified according to the type of a problem. This means that certain optimization problems are preferred or even unique for a chosen type of a problem and almost useless in another type of problems. As far as the numerical prototyping methods have been widely developed, there appeared a need for advanced numerical algorithms, which can solve the optimization problems with many objectives. From the mathematical point of view the optimization problem can be defined as follows:

$$\begin{gathered} \min f(\mathbf{X}), \quad for \quad \mathbf{X} = (x_1, x_2, \ldots, x_n)^T \\ for \\ c_i(\mathbf{X}) = 0,\ i = 1,2,\ldots,m \\ c_i(\mathbf{X}) \geq 0,\ i = m+1,\ldots,n \end{gathered} \tag{1}$$

where $f(\mathbf{X})$ is the objective function, $\mathbf{X}$ is the column vector of n independent input variables while $c_i(\mathbf{X})$ are the defined constraints of the input variables. Due to a vast number of the optimization algorithms and different problems there is a need for a proper selection of an optimization algorithm according to the optimization problem, which would be capable of reducing e.g. total number of experiments and differentiate between local and global extreme.

Global optimization is a technique of finding absolutely the best solution (parameter, set of parameters) that optimize an objective function (or many functions) in reference to the whole design space. It means that with high probability we should not be aware that the algorithm will give us the solution located in the local extreme. There are many global optimization algorithms. The best known are: Branch and bound, Monte Carlo sampling, Stochastic tunneling, Differential evolution, Simulated annealing, Evolutionary algorithms (e.g. genetic algorithms), Memetic algorithms, Colony optimization. Every algorithm of global optimization, whenever it belongs to stochastic or deterministic methods, generates a sequence of successive

approximations of the optimal solution. After the set of iterations, the algorithm gives as a result the best possible solution of given problem, as shown in the Figure 7a [8].



a. b.

Figure 7. Local v.s. global minimum problem (a) and the single v.s. multi objective problem (b).

In complex tasks there is a need for finding a solution that satisfies more than one objective function (the goal of optimization). In such cases we deal with the multi-objective optimization, as shown in the Figure 7b. In engineering applications the multi-objective optimal solution can be formulated in a form of a set, which is optimal in the so-called Pareto sense. The Pareto set (or Pareto front) is a set of alternative allocations and a set of individuals, where a movement from one allocation to another that can make at least one individual better off, without making any other individual worse off, as shown in the Figure 8 [8].

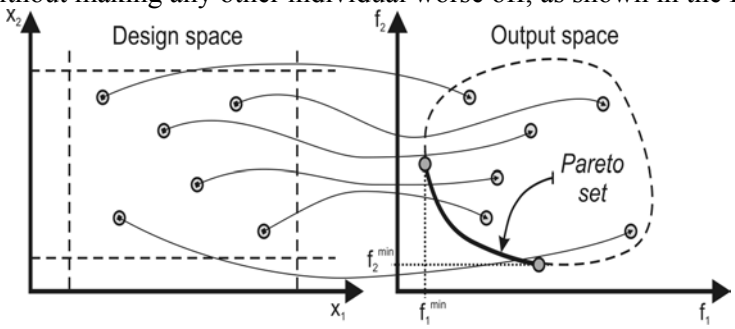


Figure 8. The Pareto set (front) [8].

3. Conclusions

The current paper presents different aspects of numerical prototyping in electronic packaging. Nowadays in most of the leading electronic companies it is a common practise to use numerical prototyping methods and tools. The reason for that is on one hand short-time-to-market, enhanced functionality and improved quality but on the second hand the improved profitability of electronic industry. Actually in order to achieve the above goals it is required to master advanced thermo-mechanical modelling methods including multi-physcis problems and advanced numerical prototyping algorithms.

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