07/71

ISSE 2007

30th International Spring Seminar on Electronics Technology 2007

Abstracts Proceedings

Emerging Technologies for Electronics Packaging
Technical University of Cluj-Napoca, Cluj-Napoca, ROMANIA
9th -13th May 2007

IEEE

CPMT
IEEE COMPONENTS, PACKAGING AND MANUFACTURING TECHNOLOGY SOCIETY

NOKIA
CONNECTING PEOPLE

MINISTERUL EDUCAȚIEI ȘI CERCETĂRII
UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA

Computational Approach for Reliable and Robust System-in-Package Design

Stoyan Stoyanov[1)], Chris Bailey[1)], Nadia Strusevich[1)] and Jean-Marc Yannou[2)]

[1)] School of Computing and Mathematical Sciences, University of Greenwich,
30 Park Row, Greenwich, London SE10 9LS, UK

[2)] NXP, 2 Rue de la Girafe, BP 5120, 14079 Caen, Cedex 5, France

E-mail: s.stoyanov@gre.ac.uk Phone: +44 (0)20 8331 8520 Fax: +44 (0)20 8331 8665

***Abstract**: A computational modelling approach integrated with optimisation and statistical methods that can aid the development of reliable and robust electronic packages and systems is presented. The Design for Reliability methodology is demonstrated for the design of a SiP structure. In this study the focus is on the procedure for representing the uncertainties in the package design parameters, their impact on reliability and robustness of the package design and how these can be included in the design optimisation modelling framework. The analysis of thermo-mechanical behaviour of the package is conducted using non-linear transient finite element simulations. Key system responses of interest, the fatigue life-time of the lead-free solder interconnects and warpage of the package, are predicted and used subsequently for design purposes. The design tasks are to identify the optimal SiP designs by varying several package input parameters so that the reliability and the robustness of the package are improved and in the same time specified performance criteria are also satisfied.*

1. INTRODUCTION

The 3D micro integration design concept of the SiP structures and the increased package complexity/functionality combined with shorter design development cycles is resulting in a decreased knowledge about the performance, reliability and robustness of these electronic modules [1]. System-in-Package (SiP) technology was developed to provide fully functional electronic systems and sub-systems that integrate several functionally different devices, optical, MEMS, sensors and other components into a single package. A particular issue of concern is how these aspects might be influenced and to what degree by the uncertainties associated with package design input parameters. Having the right tools and strategies to support the design specification process is critical requirement for the success of the technology. The goal is to ensure that a package design will provide the required reliability despite the degree of performance variation due to the uncertainty of the design inputs and their propagation into the actual response characteristics.

Simulation based optimisation for virtual design prototyping of various electronic packages and manufacturing processes has proven as an effective approach for process characterisation and product development at the early design stages [2-4]. Normally, these strategies are used to obtain the deterministic optimal package design based on the variation of a number of input parameters so that imposed constraints and design requirements are satisfied.

However, in reality such optimal package design, from deterministic point of view, may be far from a reliable, safe and robust design solution. The reason for this are the uncertainties associated with design parameters. It is very difficult and often impossible to control such existing variations. These tolerances and variations of the input design parameters may have significant impact on the system behaviour and can lead to variations and scatter of the response parameters that define the target requirements for performance and reliability. In order to ensure reliability and robustness of the designed system the uncertainties associated with the input parameters must be taken into account so that the optimal solution always meets the design constraints despite of the existing variations in the system/process response parameters.

This paper puts emphasis on three key aspects of the Design for Reliability methodology: (1) the development of reduced order models for fast analysis evaluations using Finite Element Analysis, Design of Experiments and Response Surface Modelling, (2) modelling of the uncertainties of the SiP design inputs and responses, and (3) optimal SiP design identification through reliability-driven and robustness-driven numerical optimisation.

2. Computational Analysis of SiP Thermo-Mechanical Behaviour and Reliability

The structure under investigation is a stacked dies SiP. The active die is flipped onto the passive die. The board level solder joints are designed in two peripheral rows along each side of the passive die Figure 1 illustrates the SiP. This SiP component is then placed on a printed circuit board (PCB). To improve the thermo-mechanical reliability of the board level solder joints, underfill material is used to fill the gap between the PCB and the passive die.

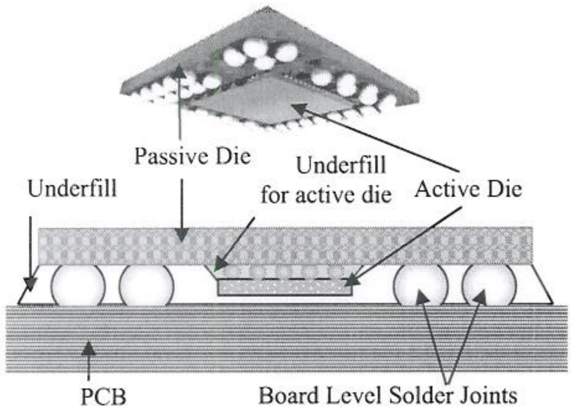


Fig. 1. SiP structure.

Table 1 details some of the dimensions of the SiP assembly. The second column specifies the geometry of the nominal (or initial) design of the SiP while the third column of the table provides details on some possible design variations of the SiP assembly parameters that are feasible to implement.

System-in-Package Design Variables	Nominal Values [mm]	Un-scaled Limits [mm]	Scaled Limits (dimensionless)
PCB Thickness	0.8	0.80 to 1.20	-1 to 1
Stand-off Height of Solder Joints	0.21	0.21 to 0.26	-1 to 1
Passive Die Thickness	0.15	0.15 to 0.25	-1 to 1

Tab. 1. SiP nominal design and parameter variations.

As detailed in Table 1, we will consider the following SiP design parameters (called design variables) with potential to vary from their nominal values:

1. PCB thickness (HPCB);
2. Board level solder joints stand-off-height (SOH);
3. Passive die thickness (HDIE).

By changing the value of any of these design variables, design modifications of the SiP structure can be generated. A set of values for the specified design variables that specify a particular design is referred as a *design point*.

Due to the existing symmetry in the SiP structure, it is sufficient to represent in the computer model only one-eight part of the assembly. The finite element model (1/8 of package) is shown in Figure 2.

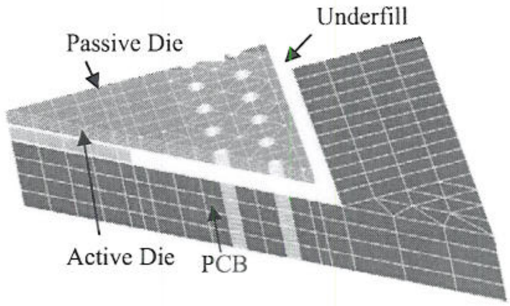


Fig. 2. Finite Element Model of SiP structure.

The thermo-mechanical response of the SiP structure is analysed under accelerated thermal cycling from -40 °C to 125 °C. Time-dependent plasticity and creep accompanied by stress relaxation for lead free solder joints are modelled using inelastic strain rate *sinh* constitutive law (Eq. 1):

$$\dot{\varepsilon}_{ij}^{cr} = A(\sinh(\alpha\,\sigma_{eff}))^{n} \exp\left(-\frac{Q}{RT}\right) \qquad (1)$$

where $\dot{\varepsilon}_{ij}^{cr}$ is inelastic strain rate, R is the gas constant, T is the temperature in Kelvin, σ_{eff} is the effective (Von Mises) stress, and all other symbols represent material related constants for Sn3.9Ag0.6Cu solder.

Inelastic strain and stress in solder joints and package deformations are predicted from the non-linear FEA. These response values are used to calculate the damage in solder joints in terms of accumulated inelastic energy density per thermal cycle *Wp*. The solder joint life prediction model (Eq. 2) is used then to correlate the damage *Wp* to life-time in terms of cycles to failure [5]:

$$N_f = (0.0014\,Wp)^{-1} \qquad (2)$$

Figure 3 illustrates the contours of the inelastic energy density across the solder joints for the initial SiP design specification.

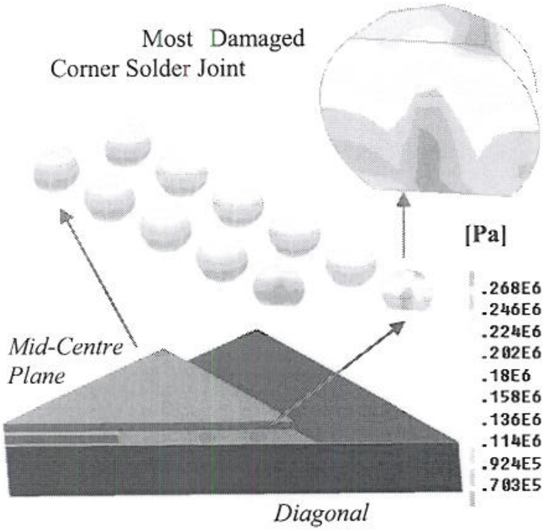


Fig. 3. Contour levels for inelastic work density across SiP solder joints (initial design) at the end of a thermal cycle.

The results from this finite element simulation show that the most critical solder joint (i.e. likely to fails first) is the one located at the corner of the package. The non-linear FEA is used also predict the deformations across the SiP assembly. A response of interest is the maximum warpage of the SiP during the thermal cycling. This quantity is defined as the difference between the minimum and maximum out-of-plane deflection of the package and is denoted as D_w. The maximum warpage occurs at the highest temperature during the thermal cycle (125°C).

Full details on the SiP structure and materials, and the modelling approach for thermo-mechanical reliability analysis can be found in reference [6].

3. Design of Experiments and Response Surface Modelling for Fast Design Evaluations

The non-linear finite element analysis outlined in the previous section is a compute intense method and is not suitable for design purposes where many design evaluations will be required during the iterative design optimisation process. In order to benefit from finite element analysis capabilities and accuracy, Reduced Order Models (ROM) based on Design of Experiments and Response Surfaces can be constructed. These models enable fast evaluations of the responses of interest for different designs [4].

The ROM modelling for the SiP structure involves the following steps:

1. Identify the experimental design points in the 3D design variables space (HPCB, SOH, HDIE).
2. Undertake finite element analysis at each design point. Obtain data for solder joint cycles to failure N_f and the maximum package warpage D_w.
3. Use the above SiP response data to construct Response Surface (RS) approximations for N_f and D_w by fitting functions to the data points (second order polynomials are demonstrated).

3.1. Design of Experiments (DoE) Method

The DoE is performed to identify the set of design points at which the finite element analysis will be undertaken to provide predictions for the SiP responses under thermal cycling. The DoE method decided in this study is the 15 points Central Composite Design (CCD). It is a combination of the factorial, axial and the central points of the 3-dimensional design space cube defined by the limits of the three design variables. The DoE points are generated using the normalised (scaled) values of the design variables in the interval [-1, 1] as indicated in

Table 1. Table 2 details the design points and the associated FEA predictions for lifetime and warpage of the SiP package.

Design Point	HPCB	SOH	HDIE	Cycles to Failure N_f	Warpage D_w [μm]
1	-1	-1	-1	2 990	11.92
2	1	1	1	2 255	7.52
3	-1	1	1	2 780	10.75
4	1	-1	-1	2 409	7.93
5	-1	-1	1	2 809	11.55
6	1	1	-1	2 437	7.35
7	-1	1	-1	2 973	11.05
8	1	-1	1	2 232	8.10
9	0	0	-1	2 659	9.23
10	0	0	1	2 480	9.24
11	0	-1	0	2 537	9.68
12	0	1	0	2 542	8.99
13	-1	0	0	2 877	11.38
14	1	0	0	2 319	7.77
15	0	0	0	2 548	9.31

Tab. 2. The 15 scaled points of CCD and SiP response.

3.2. Response Surface (RS) Modelling

After obtaining the SiP responses at the experimental design points as detailed above, the next stage in the modelling procedure is to construct approximation models to the solder joint cycles to failure (life-time) and SiP warpage. Second order polynomials are used to fit the data in Table 2 by conducting least square techniques. The RS models can be used to undertake evaluations of different design points without running any compute intensive finite element simulations.

The qualities of the RS polynomial approximations are evaluated by number of techniques for estimating their predictive power and accuracy. These include analysis of the calculated efficiency measures and Analysis of Variance. Figure 4 shows the RS terms (polynomial coefficients) for life-time response. This graph shows how sensitive is this response to variations in the values of the design variables. Most influential is the thickness of the PCB (linear term) followed by passive die thickness (linear term), etc.

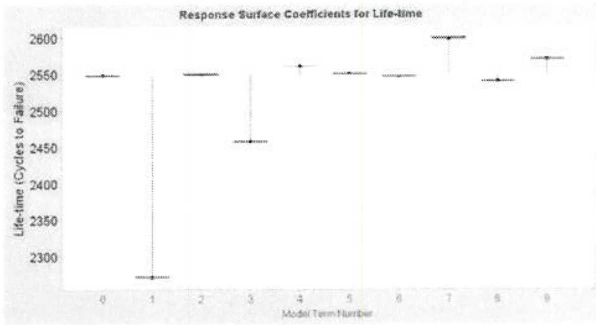


Fig. 4. RS Model terms for life-time response.

4. SiP Design Optimisation

The following design problem is formulated:

<u>*Minimise*</u> Warpage of SiP, D_w (3.0)

<u>*Subject to*</u>:

(1) Life-time $N_f \geq 2\,700$ (3.1)

(2) SOH + HDIE ≤ 0.40 mm (3.2)

(3) $0.8 \leq$ HPCB ≤ 1.2 mm (3.3)

(4) $0.21 \leq$ SOH ≤ 0.26 mm (3.4)

(5) $0.15 \leq$ HDIE ≤ 0.25 mm (3.5)

The design task (3) requires a solution for which the warpage of the package is minimised (3.0) while satisfying the life-time constraint (3.1). An additional constraint (3.2) is included in the design formulation. It requires the total thickness of the SiP package to be less than or equal to 400 microns. Constraints (3.3)-(3.5) account for the design variable limits. In this study, a design for the SiP is defined as *reliable* if it satisfies the constraints (3.1)-(3.2) given in the formulation of the design problem (3).

Normally the distribution of the probabilistic input design variables is known and can be specified through certain distribution parameters. In this study the variation is defined by Gaussian distribution and uses two parameters, the mean value and the standard deviation. The following standard deviations specify the uncertainty of the SiP design variables:

a) HPCB: standard deviation $\sigma_{HPCB} = 16$ μm;

b) SOH: standard deviation $\sigma_{SOH} = 2$ μm;

c) HDIE: standard deviation $\sigma_{HDIE} = 2.5$ μm;

The uncertainty properties of the responses are usually unknown. Therefore, when uncertainties are included in the design optimisation task, we need to estimate the random properties of the responses. Different methods can be used to obtain this information. One way is to calculate the response mean value and standard deviation and to use this information to judge the probability of failure with respect to that response. The most common simulation method is to run a Monte Carlo Simulation [7] which is technique used in this study.

4.1. Design Optimisation with Uncertainties - Probabilistic Optimisation for Reliable Design

In reliability based optimisation the aim is to account for the variations of the responses that define the reliable design domain and to ensure that the deterministic optimal solution is moved from the boundary of the active constraints inside the feasible domain. Therefore, the aim is to minimise or satisfy constraints that involve system responses and related probability of failure. This reliable optimum design is called a probabilistic optimum. To define the probabilistic optimum one must specify what probability of failure will be acceptable.

To demonstrate the reliability based design optimisation strategy, the following re-formulation of the design task (3) is given:

Find values of HPCB, SOH and HDIE that

<u>*Minimise*</u> Warpage of SiP, D_w (4.0)

<u>*Subject to*</u>:

(1) P(Life-time $N_f \leq 2\,700) \leq 0.05$ (4.1)

(2) P(SOH + HDIE ≥ 0.40 mm) ≤ 0.05 (4.2)

(3) $0.8 \leq$ HPCB≤ 1.2 mm (4.3a)

Standard deviation $\sigma_{HPCB} = 16\ \mu m$ (4.3b)

(4) $0.21 \leq$ SOH ≤ 0.26 mm (4.4a)

Standard deviation $\sigma_{SOH} = 2\ \mu m$ (4.4b)

(5) $0.15 \leq$ HDIE ≤ 0.25 mm (4.5a)

Standard deviation $\sigma_{HDIE} = 2.5\ \mu m$ (4.5b)

The solution of this optimisation problem will account for the variation of the input design variables (the constraints (4.3a)-(4.5b)). The constraint (4.1) states that the probability of the fatigue life being less than or equal to 2700 cycles to failure must be no greater than 0.05 (i.e. 5 % probability of failure limit with respect to the life-time requirement). Similarly, the constraint (4.2) is re-formulated to represent a reliability requirement on the package thickness, i.e. the probability of SiP thickness (SOH+HDIE) becoming great than or equal to 400 microns must be no greater than 0.05. By solving this problem we can find a solution (the probabilistic optimum) which, despite the uncertainty of the input parameters, will be always 95 % reliable. This reliability is with respect to design constraints (3.1) and (3.2).

The above optimisation problem is defined and solved using VisualDOC [7]. The numerical optimisation solution procedure incorporates also Monte Carlo simulations at each of the design optimisation iterations in order to evaluate the probabilities of failure as defined in (4.1) and (4.2). The solution of the design task (4) is reported in Table 3, Column (A).

4.2. Design Optimisation with Uncertainties - Probabilistic Optimisation for Robust Design

For robust design one must ensure the standard deviation of the package response under observation is minimised. Let's assume the reliability of solder joints and the minimisation of the warpage are issues of less importance. For example, reliability of SiP of 1000 cycles only is required (not 2700) and the warpage of the package must not be minimized but instead kept below a limit of 11 μm. The emphasis is now placed on the robustness with respect to cycles to failure. The objective is to minimise the variation of this response, i.e. a task equivalent to minimising the standard deviation of the package cycles to failure. The robustness driven design optimisation task is:

Find values of HPCB, SOH and HDIE that

<u>*Minimise*</u> Standard deviation of N_f (5.0)

<u>*Subject to*</u>:

(1) P(Life-time $N_f \leq 1\,000) \leq 0.05$ (5.1)

(2) P(SOH + HDIE ≥ 0.40 mm) ≤ 0.05 (5.2)

(3) Warpage of SiP, $D_w \leq 11\ \mu m$ (5.3)

(4) $0.8 \leq$ HPCB≤ 1.2 mm (5.4a)

Standard deviation $\sigma_{HPCB} = 16\ \mu m$ (5.4b)

(5) $0.21 \leq$ SOH ≤ 0.26 mm (5.5a)

Standard deviation $\sigma_{SOH} = 2\ \mu m$ (5.5b)

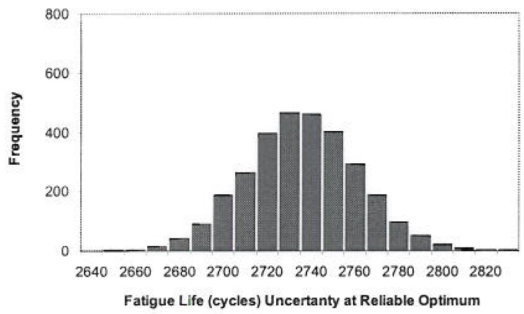
(6) $0.15 \leq$ HDIE ≤ 0.25 mm (5.6a)

Standard deviation $\sigma_{HDIE} = 2.5\ \mu m$ (5.6b)

The solution of this probabilistic task is found using again Monte Carlo probabilistic optimisation. For the optimal robust design the standard deviation of the life-time response is 14 cycles. This compares with 25 cycles for the reliable optimum in task (4). The optimal solution of the design task (5) is reported in Table 3, Column (B).

	(A) Probabilistic Reliable Optimum	(B) Probabilistic Robust Optimum
HPCB [mm]	0.945	1.200
SOH [mm]	0.242	0.239
HDIE [mm]	0.150	0.150
Warpage D_w [µm]	9.721	7.552
Life-time N_f [cycles]	2 741	2 433
P(Life-time $N_f \leq$ limit)	0.05	0.00
SiP thickness SOH+HDIE [mm]	0.392	0.389
P(SOH+HDIE ≥0.40 mm)	0.00	0.00
Standard deviation of Life-time N_f [cycles]	25	14

Tab. 3. Reliable and robust probabilistic optimum.



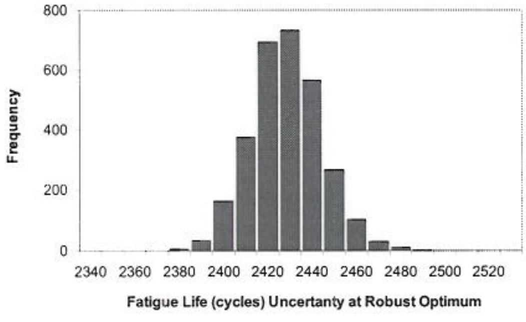


Fig. 5. Monte Carlo simulation (3000 points) and variation of fatigue life values for reliable and robust optimum.

Figure 5 shows the spread of the fatigue life values at the reliable optimum, the solution of task (4), and at the robust optimum obtain as the solution of task (5).

5. CONCLUSIONS

This paper has outlined a Design for Reliability methodology. The optimal solutions with respect to reliability and robustness have been found in a very efficient and automated way. The concept of exploiting reduced order models based on response surface modelling and design of experiments techniques has been also incorporated in the calculation procedure.

ACKNOWLEDGMENTS

This work was financially supported by the UK Innovative electronics Manufacturing Research Centre (IeMRC) through Design for Manufacture for SiP project. Special thanks are extended to our academic partner Lancaster University and our industrial collaborators: NXP, Flomerics Ltd, Coventor and SELEX Sensors and Airborne Systems.

REFERENCES

[1] Tai, K.L, "System-In-Package (SIP): Challenges and Opportunities," *Proceedings of Asia and South Pacific Design Automation Conference (ASP-DAC'00)*, Yokohama, Japan, 2000, pp. 191-196.

[2] Vanderplaats, G. N., Numerical Optimisation Techniques for Engineering Design: with Applications, VR&D, Colorado Springs (1999).

[3] Zhang, G Q, Maessen, P, Bisschop, J, Janssen, J, Kuper, F and Ernst, L, "Virtual Thermo-Mechanical prototyping of Microelectronics – the Challenges for Mechanics Professionals", *Proceedings of EuroSIME*, 2001, pp. 21-24.

[4] Stoyanov, S., Optimisation Modelling for Microelectronics Packaging and Product Design, PhD Thesis, University of Greenwich, London, UK, 2004.

[5] Syed, A, "Accumulated Creep Strain and Energy Density Based Thermal Fatigue Life Prediction Models for SnAgCu Solder Joints", *Proceedings of the 54-th ECTC*, Las Vegas, USA, June 2004, pp. 737-746.

[6] N. Strusevich, S. Stoyanov, D. Liu, C. Bailey, A. Richardson, N. Dumas, J.M. Yannou and V. Georgel, "Modelling the Behavior of Solder Joints for Wafer Level SiP", *Proceedings of the 8th EPTC*, Singapore, 6-8 December 2006, pp. 127-132

[7] VR&D VisualDOC (5.1), http://www.vrand.com