2007 International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Micro-Electronics and Micro-Systems

Proceedings of EuroSimE 2007
www.eurosime.org

EUROSIME 2007

Edited by

L.J. Ernst
G.Q. Zhang
P. Rodgers
M. Meuwissen
S. Marco
W.D. Van Driel
O. de Saint Leger

IEEE
IEEE Catalog Number: 07EX1736
ISBN: 1-4244-1105-X
Library of Congress: 2007922208

07/73

Reliability Based Design Optimisation for System-in-Package

S. Stoyanov [1], J. M. Yannou [2], C. Bailey [1], N. Strusevich [1]
[1] Centre for Numerical Modelling and Process Analysis, 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

Abstract

This paper discusses a reliability based optimisation modelling approach demonstrated for the design of a SiP structure integrated by stacking dies one upon the other. In this investigation the focus is on the strategy for handling the uncertainties in the package design inputs and their implementation into the design optimisation modelling framework. The analysis of thermo-mechanical behaviour of the package is utilised to predict the fatigue life-time of the lead-free board level solder interconnects and warpage of the package under thermal cycling. The SiP characterisation is obtained through the exploitation of Reduced Order Models (ROM) constructed using high fidelity analysis and Design of Experiments (DoE) methods. The design task is to identify the optimal SiP design specification by varying several package input parameters so that a specified target reliability of the solder joints is achieved and in the same time design requirements and package performance criteria are met.

1. Introduction

System-in-Package (SiP) technology was developed to provide fully functional electronic systems and sub-systems that integrate several functionally different devices (like IC- and RF-chips) and optical, MEMS, sensor and other components into a single package. The 3D micro integration design concept of the SiP structures and the increased package complexity/functionality combined with shorter times allowed for the design cycles is resulting in a decreased knowledge about the performance and the reliability of these electronic modules [1]. A major challenge is to understand the risks for failure and the associated failure modes, and to qualify the package from a reliability stand of point. Another aspect of the SiP design challenge is to assess and take into account the thermal, mechanical and electrical behaviour of a particular SiP module so that the structure can be optimised before it is actually manufactured. Unfortunately, there is little design knowledge and experience about SiP, with the options for real testing that can aid the design for manufacture being also limited.

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]. Computational modelling and simulation approach that exploits numerical analysis tools and methods (such as Finite Element Analysis or reduced order models) integrated with optimisation techniques can aid the identification of the optimal design/process specification and the formulation of design rules for optimal performance/reliability of the developed SiP structures. The virtual design optimisation approach is a strategy that can deliver 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 and safe design solution. The reason for this is that the design of a real system, including the design of a SiP structure, often includes parameters that have uncertainties associated with them. This is a result of the natural variations that exist in the manufacturing and/or operational process parameters (e.g. operational temperature, humidity, etc), the tolerances in the dimensions of the manufactured structures, the physical properties of the materials, etc. 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. Therefore, the uncertainties in the responses/behaviour of the deterministic optimal design can result in performance that violates the specified requirements and reliability criteria. In order to ensure reliability of the designed system the uncertainties associated with the input parameters must be taken into account and brought into the modelling framework so that the optimal solution always meets the design constraints despite of the existing variations in the system/process response parameters.

Three key aspects are emphasised and discussed in the paper: (1) thermo-mechanical life-time assessment of the lead-free (SAC) SiP interconnects and warpage of the package using finite element analysis, (2) modelling of the uncertainties of the SiP design inputs and responses, and (3) optimal SiP design identification through reliability-driven numerical optimisation. The optimisation modelling incorporates the development of Reduced Order Models (ROM) for fast evaluation and assessment of the SiP thermo-mechanical response parameters. The ROM are developed using the results from high fidelity analysis (Finite Element Analysis) conducted for limited number of experimental SiP design configurations and the relevant response surface modelling.

1-4244-1105-X/07/$25.00 ©2007 IEEE

2. SiP Structure and Design Parameters

2.1. Geometric Details

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 and are located on the same side of the passive die where the active die is placed. The external row of joints is 11x11 and the second row had 9x9 configuration pattern. The pitch size used to distribute the solder joints is 0.5 mm. Figure 1 illustrates the SiP.

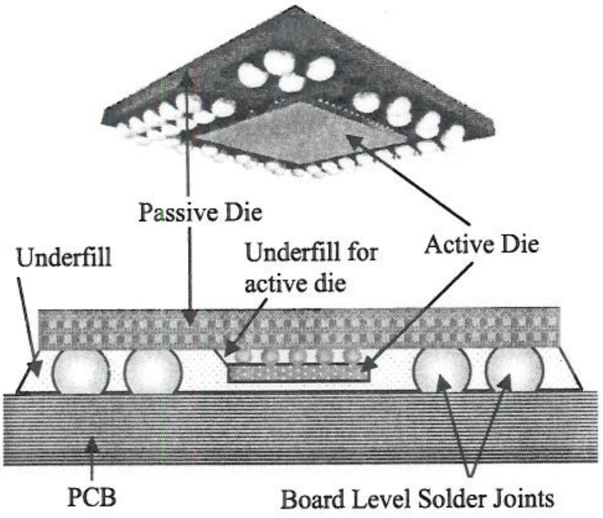

Figure 1: SiP structure.

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.

Table I details some of the dimensions of the SiP assembly.

Table I. SiP nominal design and parameter variations.

System in Package Structure	**Nominal (Initial) Design**	**Design Parameter Variation**
Active Die Dimensions [mm]	Area: 2.26 x 2.26 Thickness: 0.15	none none
Passive Die Dimensions [mm]	Area: 5.7 x 5.7 Thickness: 0.15	none 0.15 - 0.25
PCB Thickness [mm]	0.8	0.8-1.2
Stand-off Height of Board Level Solder Joints [µm]	210	210 - 260
I/O pitch [mm]	0.5	none
Number I/O (two rows, peripherally)	11x11 (1st row) 9x9 (2nd row)	none none

In Table I, 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.

As detailed in Table I, we will consider the following SiP design parameters 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).

Because any of these design parameters can be changed within the specified lower and upper bounds, we call them *design variables*. The bounds which define the variation limits for each of the three design variables are specified in the third column of Table I. Note that the term variation here is not related to the uncertainty qualification but has the meaning of limits for changing the value of the variable. 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 define a certain design is named shortly 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 one-eight symmetric models lower significantly the compute times for the undertaken simulations. The symmetry planes are taken into account in the 1/8 modelled part by using the appropriate boundary conditions set up for the analysis.

All solder interconnects inside the modelled one-eight part of the SiP are taken into account and are included into the finite element model representation. Once the geometry and all model components are defined, a finite element mesh grid is generated throughout the whole domain of the model. The finite element model (1/8 of package) is shown in Figure 2.

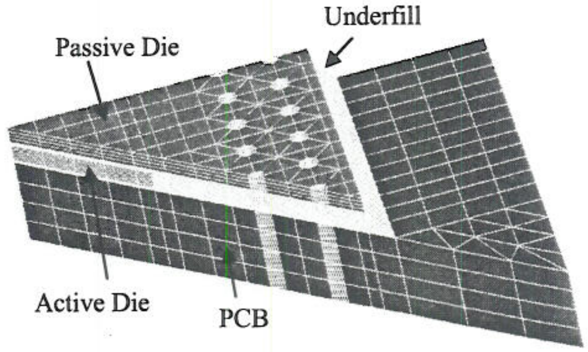

Figure 2: 1/8 Finite element model of SiP.

2.2. Material Models

In this modelling study, non-linear material behaviour is considered for the solder material; the rest of the materials are assumed to behave in an elastic manner.

Temperature dependent properties of the SiP materials are also incorporated in this analysis. Orthotropic coefficient of thermal expansion is implemented for the organic composite package carrier (the PCB). The detailed properties of all materials are reported in Table II.

Table II. SiP materials and their properties.

Materials	*CTE* $(10^{-6}/{}^{\circ}C)$	Young's Modulus E (MPa)	Poisson ratio ν
PCB	16.0 (xy) 52.4 (z)	25,000	0.3
Solder : SnAgCu	20.0	61251-58.5T(°K)	0.36
Die: Silica	2.3	169,000	0.26
Underfill Epoxy	28.0	3,500	0.3

Under temperature cycling the solder materials experience deformations due to time-dependent plasticity and creep accompanied by stress relaxation [5, 6]. The cycling stresses are result of the coefficient of thermal expansion miss-match between the materials used in the package. The inelastic strain rate of the solder material is modelled in this study using the widely accepted *sinh* constitutive law. The inelastic strain rate $\dot{\varepsilon}_{ij}^{cr}$ using *sinh* expression is given as

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

where 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 properties. For Sn3.9Ag0.6Cu solder alloy the creep constants are taken from Schubert et al [7] and have the following values: $A = 277984\,s^{-1}$, $\alpha = 0.02447\,MPa^{-1}$, $n = 6.41$ and $Q = 6500R$.

To enhance the overall reliability of the SiP structure, an underfill material is utilized. The underfill selected in this investigation has coefficient of thermal expansion *CTE*=28 ppm/°C and Young's Modulus *E*=3.5GPa.

2.3. Computational Analysis of SiP Thermo-Mechanical Behaviour and Life-time Modelling

The thermo-mechanical response of the SiP structure is analysed under accelerated thermal cycling. A cycle lasts for 2 hours and consists of four stages: ramp up from -40 °C to 125 °C for 45 minutes; hold at the higher temperature for 15 minutes; ramp down to -40 °C for 45 minutes; and finally hold at -40 °C for 15 minutes. In this study we assume a stress-free state for the SiP at 20°C; this is also the starting temperature for the thermal cycling.

The time dependent inelastic deformations are highly non-linear; hence transient analysis is required to simulate the solder behaviour. In such a transient analysis, the time domain of the thermal cycle is divided into time steps with thermal load at any time step the temperature change between this step and the previous step.

Inelastic strain and stress in Sn3.9Ag0.6Cu solder joints and package deformations are predicted from the non-linear FEA. These response values are used to calculate the damage in solder joints and to judge the thermal fatigue reliability of the package interconnects. In this study, the volume weighted average value, *Wp*, of the accumulated creep energy density per thermal cycle in the solder joints is considered. The *Wp* is also known as the inelastic work density and will be referred shortly as the *damage*. This quantity is used subsequently in a life-time model to make prediction for the solder joints mean cycles to failure.

The damage parameter *Wp* is calculated from

$$Wp = \sum_{\Delta t} \frac{\sum_{i=1}^{IP} \int_{Vi} \sigma^{T} (\Delta\varepsilon^{vp}) dV}{\sum_{i=1}^{IP} \int_{Vi} dV} \tag{2}$$

where the outer sum is over the time steps Δt that cover a full thermal cycle, "*IP*" is the number of the integration points used to calculate the inelastic work density, V_i is the volume associated with the integration point with index "*i*", σ is the stress tensor, $\Delta\varepsilon^{vp}$ is the tensor of the visco-plastic strain increment for Δt. Accumulated inelastic energy density per cycle in the most critical solder joint is calculated over a thin layer of solder mesh elements at the passive die interface (the volume V in Eq. 2). This is the critical location within the solder joint where it was found the crack will initiate and propagate.

A number of simplifications and assumptions are made in the analysis. All initial stresses in the package are neglected. The damage parameter *Wp* is calculated from the results associated with the second thermal cycle that is found to provide a stabilized hysteresis loop. Modelling the temperature cycling regime assumes an isothermal loading throughout the package. Finally, perfect adhesion between all materials is assumed.

The SnAgCu solder joint life prediction model [8] used to correlate the damage *Wp* to life-time in terms of cycles to failure is:

$$N_f = (0.0014\,Wp)^{-1} \tag{3}$$

The above life prediction model is function of the accumulated creep energy density per cycle *Wp* (in MPa) and predicts the mean life N_f of SnAgCu solder joints in terms of number of cycles to failure. The constants in Equation 3 are obtained by fitting a linear regression model to sets of experimental data assuming the hyperbolic sine constitutive equation for the solder creep behaviour [8].

The software package PHYSICA [9] is used to model and predict the evolution of thermal stresses and strains in this SiP package during a thermal cycle. Figure 3 illustrates the contours of the inelastic work density across the solder joints associated with the 1/8 part of the constructed finite element model of the SiP with the initial design specification. 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. It was also found that variations in the values of the analyzed design parameters do not affect the location of the most exposed to the creep damage joint and it always stays at the corner of the SiP structure.

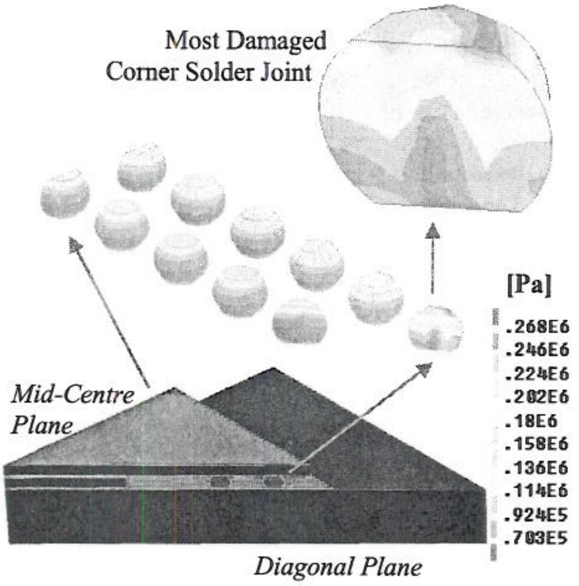

Figure 3: Contour levels for inelastic work density across SiP solder joints (initial design) at the end of a thermal cycle.

The non-linear FEA provides us also with predictions for 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. It is found that the minimum and maximum out-of-plane displacements are occurring at centre and at the corner of the SiP passive die respectively. The maximum warpage occurs at the highest temperature during the thermal cycle (125°C). Figure 4 illustrates the warpage of the SiP for the initial design (deformation is magnified by factor 50).

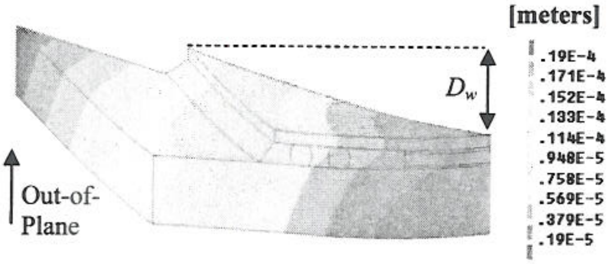

Figure 4: Contour levels of the out-of plane deformations across SiP assembly at 125°C during a thermal cycle.

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

The non-linear finite element analysis outlined in the previous section is capable of predicting the SiP responses of interest. This is a compute intense method and often is not suitable for design purposes where many design evaluations will be required during the iterative design optimisation process. However, as it was demonstrated, a finite element analysis has the advantage of predicting with great accuracy the behaviour of the analysed system.

In order to benefit from finite element analysis capabilities in the design process, reduced order models based on Design of Experiments and Response Surfaces can be constructed. These models allow us to undertake fast evaluations of the response of interest for different design specifications [4].

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

1. Identify the experimental design points in the three-dimensional design variables space (HPCB, SOH, HDIE).
2. Undertake finite element analysis at each design point (*PHYSICA* simulation). Obtain data for solder joint cycles to failure N_f (using Eq.2 and the predicted solder damage Wp) and the maximum package warpage D_w.
3. Use the above SiP response data to construct Response Surface (RS) approximation 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 response under thermal cycling. The focus here is on the cycles to failure of solder joints N_f and the maximum warpage of the package D_w. 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 way the DoE points are dealt with is to use normalised (scaled) values of the design variables in the interval [-1, 1]. In this, -1 corresponds to the lower limit of the design variable and 1 corresponds to the upper limit of the design variable. This transformation is detailed in Table III.

The design point number is given in the first column of Table IV and the design variable scaled values for each of the experimental points of the CCD are given in the next three columns of the table. After running the 15 DoE simulations, numerical predictions for the solder joints cycles to failure N_f and the maximum warpage of the package D_w become available. These predictions are detailed in the fifth and the sixth column of Table IV respectively.

Table III. Design Variable scaling.

	PCB thickness HPCB	Stand-off Height SOH	Passive Die Thickness HDIE
Un-scaled Limits [mm]	0.8 to 1.2	0.21 to 0.26	0.15 to 0.25
Scaled Limits (dimensionless)	-1 to 1	-1 to 1	-1 to 1

Table IV: The 15 scaled points of CCD and SiP response.

Design Point	HPCB	SOH	HDIE	Cycles to Failure N_f	SiP 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

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 IV by conducting least square techniques. The coefficients of the constructed RS polynomial approximations are detailed in Table V. The polynomials are based on the inputs of the scaled design variables.

The RS models can now be used to evaluate approximately the solder joints life-time and the package warpage for any design point (i.e. for any combination of values for PCB thickness, solder joint stand-off-height and passive die thickness) without running any finite element simulations. These RS models are reduced order models and can substitute the compute intensive finite element analysis as an approach for design evaluation.

Table V: RS polynomial coefficients for SiP responses (based on scaled input design variables).

	Warpage D_w RS Model	Life-time N_f RS Model
RS Polynomial Term	***Coefficient***	***Coefficient***
Constant	9.31213	2548.13333
HPCB	-1.79940	-277.70000
SOH	-0.35180	1.00000
HDIE	-0.03290	-91.20000
HPCB*SOH	0.06263	12.12500
HPCB*HDIE	0.12563	1.87500
SOH*HDIE	0.00713	-2.12500
HPCB**2	0.26233	49.83333
SOH**2	0.02333	-8.66667
HDIE**2	-0.07717	21.33333

The quality of the RS polynomial approximation is evaluated by number of techniques for estimating its predictive power and accuracy. These include analysis of the calculated efficiency measures, analysis of variance (ANOVA) and analysis of the residuals. For example, for both RS models we have found a very good predictive capability indicated by the coefficient of multiple determination, R^2_{adj} = 99.96 to 99.99%.

4. SiP Design Optimisation

If we come back to the SiP structure and the specified design variables which provide flexibility to obtain different specification for the package and the assembly, the question now is what would the optimal design be? In order to identify the optimal design specification, we need to know:

1. What are the design variables we can change in order to have different designs that then can be evaluated. In this study we have already defined the three design variables of interest (HPCB, SOH and HDIE).
2. With respect what aspect/criterion we would like to have an optimal design specification (i.e. which aspect of the SiP we want to optimise).
3. What are the requirements this optimal design must satisfy (e.g. reliability, or any other).

Once the above questions are answered, we can formulate the design task as a mathematical problem and solve it using optimisation techniques.

4.1 Deterministic Design Optimisation

For our problem, the following formulation of the design task is given:

Find values of the design variables HPCB, SOH and HDIE that

Minimise Warpage of SiP, D_w (4.0)

Subject to:

(1) Life-time $N_f \geq 2\,700$ (4.1)
(2) SOH + HDIE ≤ 0.40 mm (4.2)
(3) $0.8 \leq$ HPCB ≤ 1.2 mm (4.3)
(4) $0.21 \leq$ SOH ≤ 0.26 mm (4.4)
(5) $0.15 \leq$ HDIE ≤ 0.25 mm (4.5)

The design task (4) requires a solution for which the warpage of the package is minimised (4.0) while satisfying the life-time constraint (4.1). The constraint (4.1) states a requirement for the solder joints fatigue mean life to be no less than 2700 cycles. An additional constraint (4.2) 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 (4.3)-(4.5) account for the design variable limits.

In the above optimisation task the warpage and life-time evaluation of different designs during the iterative solution procedure exploits the representative RS models developed for the two responses. No calls to finite element analysis software are performed at this stage. The above optimisation problem is defined and solved using VisualDOC [10]. The optimal solution has been found first by using gradient optimisation numerical techniques [10]. To verify that the found optimal design is the true global optimum, a non-gradient optimisation of the same design task was performed. It confirmed the already identified optimal solution.

Based on the solution of the design task (4), a deterministic optimal solution for the design of the SiP structure has been found. The optimal design results are reported in Table VI. The optimal passive die thickness is 150 μm (value of the lower bound) and the optimal values for PCB thickness and solder joint stand-off- height are respectively 0.971 mm and 250 μm. Note, at this optimal design specification for the SiP assembly the life-time constraint (4.1) and the SiP thickness constraint (4.2) become both *active* (i.e. have values equal to the imposed limits and satisfy the constraints as equality). Any effort for further improvement of the objective (4.0), i.e. D_w minimisation, will cause one or both of the constraints to become violated. This would result in a design specification outside the feasible domain of (4.1)-(4.5).

Table VI: Deterministic optimum.

	Initial	Optimal
HPCB [mm]	0.800	0.971
SOH [mm]	0.210	0.250
HDIE [mm]	0.150	0.150
Warpage D_w [μm]	11.90	9.341
Life-time N_f [cycles]	2990	2700
SiP thickness, SOH+HDIE [mm]	0.360	0.400

4.2 Uncertainty Modelling and its Effect on Reliability

A deterministic optimum specification is not necessary a reliable optimal solution. The reason for this is in the uncertainty which normally is associated with the design variables. Such variations from the deterministic optimal values can lead to SiP structures that fall outside the failure free design domain. In this study, a design for the SiP is defined as *reliable* if it satisfies the constraints (4.1)-(4.2) given in the formulation of the design problem (4). Here we will not be concerned if the limit constraints (4.3)-(4.5) are violated as a result of the design variable uncertainty. We are going to assume feasible SiP design specifications at and near the design variable limits. However, there is no limitation to consider and include in the reliable domain formulation all or any of the design variable limit constraints.

In this study we consider variations (uncertainty related) for the design variables which follow and can be described using normal (Gaussian) distribution. Normally the distribution of the probabilistic input design variables is known and can be specified through certain distribution parameters. In this study the distribution is defined by two parameters, the mean value and the standard deviation. The following standard deviations define the distributions that account for the variable uncertainty:

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;

Figure 5 shows the probability density function (PDF) for the HPCB scaled design variable with mean value 0 (un-scaled value of 1 mm). It also shows the cumulative density function (CDF) for the same scaled variable. In a similar manner, PDFs and CDFs functions can be considered for the other two design variables.

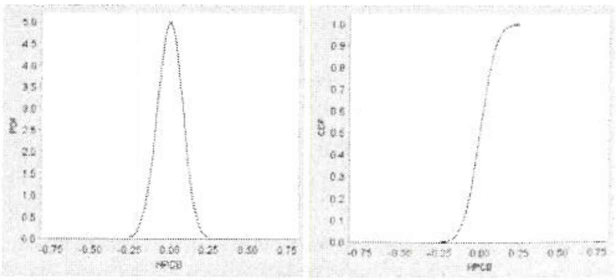

Figure 5: Probability and cumulative density functions for mean scaled value 0 and scaled standard deviation 0.08.

The uncertainties of the input parameters will affect the responses of the SiP assembly and will lead to variations in the values of the responses of interest. In particular, the life-time N_f and the thickness of the package values will follow a certain distribution profile as a result of the variation. In general, the uncertainty properties of the responses are 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 [10]. This is the technique used in this study. The basic idea is, for fixed nominal values of the design input variables, to generate large number of random design points according to the distributions of the probabilistic input variables. The values of the design input variables of the generated points in the set represent the variations due to uncertainty from the fixed nominal values. For each of these points the values of the responses of interest are calculated. The values of the fatigue life and warpage response in the SiP design task are calculated using the Response Surface models.

4.3 Design Optimisation with Uncertainties (Probabilistic Optimisation)

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 (4) is given:

Find values of the design variables HPCB, SOH and HDIE that

Minimise Warpage of SiP, D_w (5.0)

Subject to:

(1) P(Life-time $N_f \leq 2\,700) \leq 0.05$ (5.1)

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

(3) $0.8 \leq$ HPCB ≤ 1.2 mm (5.3a)

Standard deviation $\sigma_{HPCB} = 16\ \mu m$ (5.3b)

(4) $0.21 \leq$ SOH ≤ 0.26 mm (5.4a)

Standard deviation $\sigma_{SOH} = 2\ \mu m$ (5.4b)

(5) $0.15 \leq$ HDIE ≤ 0.25 mm (5.5a)

Standard deviation $\sigma_{HDIE} = 2.5\ \mu m$ (5.5b)

As evident from the above formulation, the solution of this optimisation problem will account for the variation of the input design variables (the constraints (5.3a)-(5.5b)). The constraint (5.1) 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 (5.2) 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 (4.1) and (4.2).

VisualDOC software package has incorporated features for probabilistic design optimisation and therefore is used once again to specify and solve the design task (5). Note, the same optimisation techniques as applied in deterministic optimisation can be used to solve the probabilistic design task. However, there is some extra calculation efforts associated with running the Monte Carlo simulation at each of the design optimisation iterations in order to evaluate the probabilities of failure as defined in (5.1) and (5.2).

The solution of the design task (5) is reported in Table VII. The previously found deterministic optimum is also included in the table.

Table VII: Probabilistic optimum.

	Initial	Determ. Optimum	Probab. Optimum
HPCB [mm]	0.800	0.971	0.945
SOH [mm]	0.210	0.250	0.242
HDIE [mm]	0.150	0.150	0.150
Warpage D_w [μm]	11.90	9.341	9.721
Life-time N_f [cycles]	2990	2700	2 741
P(Life-time $N_f \leq 2\,700$)	-	0.5	0.05
SiP thickness SOH+HDIE [mm]	0.360	0.400	0.392
P(SOH+HDIE $\geq$0.40 mm)	-	0.5	0.00

The last two columns of the table compare the deterministic and probabilistic solution. It is clear that by moving the deterministic optimum from the active constraints boundary inside the feasible domain, we have compromised on the level to which our objective is minimised, the SiP warpage (from 9.341 up to 9.721 μm). However, what we have gained by doing this is that our probabilistic optimum is now 95 % reliable. This compares with 50 % reliability of the deterministic optimum. In particular, at the probabilistic optimum the cycles to failure in terms of mean value are 2741 and only 5% of the SiP structures will have life-time less than 2700 as a result of the uncertainties of the input design variables. Figure 6 shows the Monte Carlo simulation output for the life-time response at the probabilistic optimum. This run uses 3000 points to compute the life-time response standard deviation from the mean value (2741) and to estimate the probability of failure (with respect to the 2700 cycles limit).

Note that at the probabilistic optimum the probability of failure for SiP thickness constraint (5.2) becomes 0.

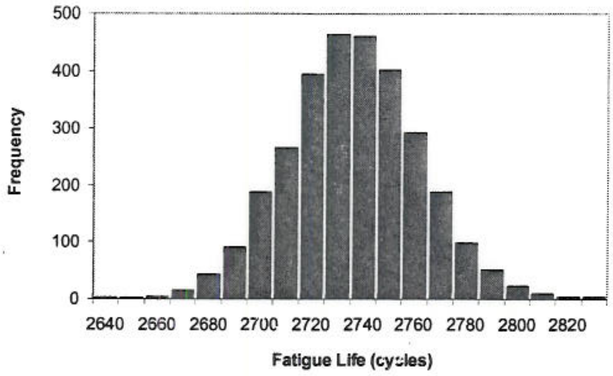

Figure 6: Monte Carlo simulations (3000 points) for fatigue life at the probabilistic optimum.

4. Conclusions

This paper has demonstrated a modelling framework for reliability based design optimisation. It is shown that the deterministic optimum might not be a reliable solution. It is important to bring into the design problem formulation probability of failure constraints. The advantage of such design approach is that it can deliver a more realistic design solution and provides the opportunity to account for the variations of the input design parameters.

A SiP structure has been optimised under a set of design constraints. A reliable design which satisfies a requirement for 95% reliability with respect to the system life-time and package thickness constraints is demonstrated. The optimal solution has 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. It was shown that the usage of reduced order models is extremely critical aspect in the implementation of the design optimisation with uncertainties approach.

Acknowledgments

This work was financially supported by the UK Engineering and Physical Sciences Research Council (EPSRC) and the Innovative electronics Manufacturing Research Centre (IeMRC) through Design for Manufacture for SiP project. Special thanks are extended to our academic parthner Lancaster University and our industrial collaborators: NXP Semiconductors, 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. Hua, F., "Pb-free Solder Challenges in Electronic Packaging and Assembly", *The 53-rd IEEE Electronic Components and Technology Conference Proceedings*, New Orleans, Louisiana, USA, June 2003, pp. 58-63.
6. Lau, J. H., "Design, Materials, Process and Reliability of Lead-free Solders for Robust IC Electronic and Optoelectronic Packaging", *Short Course Notes of the 5-th Electronics Packaging Technology Conference*, Singapore, December 2003.
7. Schubert, A., *et al*, "Reliability Assessment of Flip-Chip Assemblies with Lead-Free Solder Alloys", *The 52-th IEEE Electronic Components and Technology Conference Proceedings*, San Diego, CA, USA, May 2002, pp. 1246-1255.
8. Syed, A, "Accumulated Creep Strain and Energy Density Based Thermal Fatigue Life Prediction Models for SnAgCu Solder Joints", *Proceedings of the 54-th Electronic Components and Technology Conference Proceedings*, Las Vegas, Nevada, USA, June 2004, pp. 737-746.
9. PHYSICA, http://www.physica.co.uk, Multi-physics Software Ltd
10. VR&D VisualDOC (Version 5.1), http://www.vrand.com