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Optimizing the Reliability of Power Electronics Module Isolation Substrates

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1. Abstract

Optimal design of a power electronics module isolation substrate is assessed using a combination of finite element structural mechanics analysis and response surface optimisation technique. Primary failure modes in power electronics modules include the loss of structural integrity in the ceramic substrate materials due to stresses induced through thermal cycling. Analysis of the influence of ceramic substrate design parameters is undertaken using a design of experiments approach. Finite element analysis is used to determine the stress distribution for each design, and the results are used to construct a quadratic response surface function. A particle swarm optimisation algorithm is then used to determine the optimal substrate design. Analysis of response surface function gradients is used to perform sensitivity analysis and develop isolation substrate design rules. The influence of design uncertainties introduced through manufacturing tolerances is assessed using a Monte-Carlo algorithm, resulting in a stress distribution histogram. The probability of failure caused by the violation of design constraints has been analyzed. Six geometric design parameters are considered in this work and the most important design parameters have been identified. Overall analysis results can be used to enhance the design and reliability of the component.

2. Keywords: Three to five key words should be typed here

Power Electronics, Reliability, Risk Mitigation, Optimization, Numerical Modelling, Finite Element, isolation substrate

3. Introduction

This paper discusses a methodology for numerically assessing the reliability of power electronics module components and enhancing understanding of the influence of design parameters on product reliability and failure risk. The Finite Element Method is used in conjunction with design of experiment and optimisation techniques to assess the impact of design variation and uncertainty within a power electronics module component. Design points in the design hyperspace are chosen using design of experiment method. Finite Element method models are used to evaluate the stresses induced within the component due to thermal-mechanical loading at these design points. Regression analysis is then used to formulate a function capturing the variation in stress resulting from variations in the design. Variation in component design can be either deliberate or unintentional. Deliberate variations result from modifications made by the design engineer to optimise the component performance. Unintentional design variation result from manufacturing imperfections, such as machining tolerances, material variations and assembly accuracy. The design analysis methodology enables the effect of variation in design parameters to be assessed. This allows the relative influence of numerous design parameters to be determined, forming design rules and increasing the design engineers’ understanding of the component. The optimal design of the component can also be determined using optimisation algorithms.

The effects of manufacturing imperfections can be captured through the use of Monte Carlo methods which generate a histogram showing variation of stresses within a single design due to uncertainty. The results obtained demonstrate that stresses within a power electronics module component can be determined numerically. Furthermore, the relative influence of design parameters and the optimal design of the component can be determined using approximate response surface equations and optimization method. The effects of uncertainty have been analysed using a Monte-Carlo approach. The methodology presented is applicable to a wide range of engineering applications and illustrates the effects of manufacturing uncertainty in product reliability.

4. Power Electronics Modules

4.1 Overview

Power Electronics Modules (PEMs) are power electronics components that control the supply and conversion of electric powers. A PEM may perform tasks such as changing phase, voltage, current or frequency of an electrical power source. Typical functions include conversion from alternating current (AC) to direct current (DC) (rectification), conversion from DC to AC (inversion), control of voltage and control of frequency. For example in a system such as a hybrid petrol-electric vehicle, the battery cannot be connected directly to the electric drive motors that use AC. The DC current from the battery must be converted to an AC supply and regulated in a manner in which the motor power can be controlled by the driver. In the case of a hybrid vehicle an integrated gate bipolar transistor (IGBT) inverter module is used to perform this task.

PEMs are used in a very large number of applications with a high diverse set of operating requirements – module switching power varies from a few mW up to approximately 100,000 kW. The power electronics market size is currently in excess of $60 billion per annum and affects a further $1 trillion in hardware sales. Power electronics are expected to control up to 80% of all electricity used by 2010 [1]. Examples of recent new PEM applications include hybrid motor vehicles, more/all electric aircraft (in which hydraulic systems are replaced with electrical systems) and renewable energy applications such as wind turbines and solar power.

4.2 Power Module Design and Challenges

PEMs are being used in an increasing number of applications, requiring new modules to be designed for use in novel applications and in increasingly harsh operating regimes. These new applications require the performance of the modules to be pushed beyond current limits whilst retaining extremely high reliability standards. With expanding use in critical systems and continuously developing requirements it is crucial to ensure and enhance the reliability of future PEM modules. A strategy to analyse, assess and mitigate failure has been developed to this end.

A typical power module consists of several materials stacked together. The module utilises silicon semiconductor devices to perform the main power conversion tasks. Devices such as IGBTs, metal oxide semiconductor field effect transistors (MOSFETs), and thyristors are commonly used in PEMs. These semiconductor devices are mounted on an isolation substrate commonly formed from ceramic materials such as aluminium oxide (alumina) and aluminium nitride (AlN). The isolation substrate has a metal surface (known as metallisation) on at least one side, which is chemically etched to form a number of conductive tracks. The purpose of the isolation substrate is to mechanically support the semiconductor devices and to insulate various parts of the device from each other. The metallisation layer is typically about 200 micron thick and is commonly formed through direct copper bonding [2] or actively brazed copper technologies [3]. The isolation substrate is attached to a baseplate made from a thermally conductive material such as copper or metal matrix composite (MMC) for structural support. The baseplate also performs the role in temperature regulation, absorbing thermal transients and providing a route to dissipate heat out of the module. Finally, solder materials are used to bond components together. Three types of connections are used as there is a requirement to bond the semiconductor to the isolation substrate metallisation (‘chip mount-down’), to bond the isolation substrate to the baseplate (‘substrate mount-down’), and to bond busbars to the substrate.

Ancillary components of a power module include wirebonds – metal wires used to connect semiconductor devices to each other and to substrate metallisation, encapsulants to protect the devices from environmental factors such as moisture and humidity and a (normally plastic) casing to protect and enclose the device. The picture on the right of Figure 1 (courtesy SEMELAB Ltd.) shows a typical module construction. A typical 800A IGBT plastic module used in a rail traction application (courtesy Dynex Semiconductors), pictured on the left of in Figure 1, handles almost one Megawatt of electrical power (960 kVA). It dissipates about 3KW of energy as heat and is approximately 105mm by 62mm by 30mm in size.

4.3 Failure mechanisms of PEMs

PEMs may be affected by a number of differing failure mechanisms in differing operating regimes. The three primary failures suffered by PEMS are wirebond lift-off, solder joint fatigue, substrate fracture, and conductor de-lamination, and dielectric break down. Wire bonding is one of the most commonly employed interconnect technology in power electronic modules. The reliability of Al wire bonds depends on the bond strength between the Al wire and the IGBT die [4]. However, the wire bonds are susceptible to heel crack [5] failures arising from flexing due to thermal expansion or overworked bond heel during ultrasonic bonding [6]. Additional fatigue failures are caused by thermo-mechanical damage mechanisms caused by the mismatch of thermal expansion coefficients (CTE) between the aluminium wire and silicon die at the contact interface. Wirebond reliability has duly attracted a large amount of research [7,8,9].

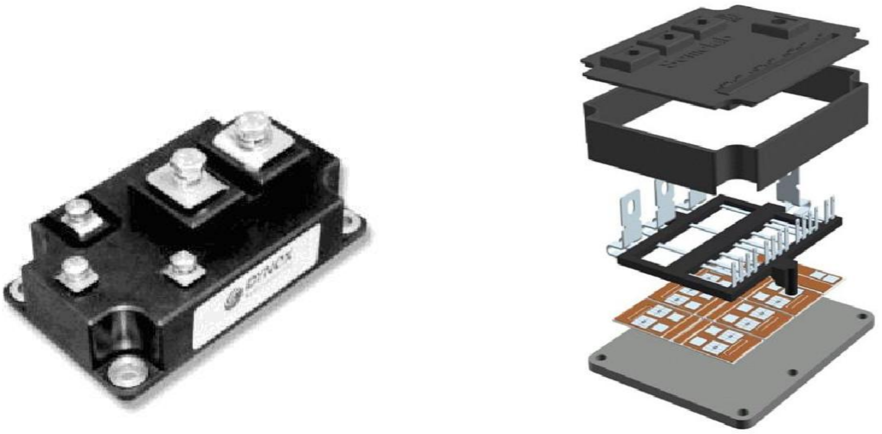

Figure 1: Typical Power Module assembly (Courtesy of Dynex Semiconductors and Semelab Ltd).

Substrate fracture and conductor de-lamination mainly occur due to fractures in the isolation substrate. Thermally induced stresses induce microscopic cracking in the microstructure of the ceramic near the boundary with the conductive copper tracks. Continued thermal cycling of the module results in elongation of the cracks until a critical scale is reached, leading rapidly to a loss of structural integrity and failure of the module. This structural failure can take the form of separation of the conductive tracks from the ceramic substrate, known as conductor de-lamination or through catastrophic failure of the brittle ceramic substrate material. The failure of the isolation substrate in this manner is commonly referred to as conchoidal fracture, illustrated in Fig. 2. A significant body of work, such as [10, 11, 12, 13], has been published analysing this process. In order to assess the influence of module design parameters have upon the operational lifetime of PEMs, a means of analysing the reliability of the module is required.

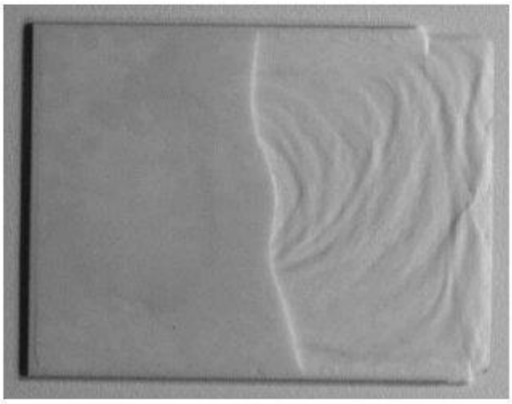

Figure 2: Conchoidal Fracture of ceramic substrate

5. Reliability Analysis

5.1 Traditional approaches

A reliability prediction estimates the service lifetime of a power electronics module as used in the field and in tests. This depends on the design of the power module and the in-service environmental, or test, conditions it is subjected to during its lifetime. Traditionally electronics component reliability prediction and qualification relies on methods that are based on historical field-return data. One of the most widely used such methods is the MIL-217 [14] reliability prediction methodology. Typically, the mean time between failures (MTBF) is given as the reliability metric. This type of calculation is based on failure rates for each component making up the device which are statistically obtained from field data. It is well documented [15, 16] that this technique can result in very poor predictions. There are other reliability prediction tools similar to MIL-217, such as telcordia [17]. In the IEEE-std-1413 [18], a guideline for selecting reliability prediction methods is detailed.

Experimentally, module reliability is assessed using accelerated life testing methods such as temperature and power cycling. Temperature cycling tests involve placing a statistically significant number of sample modules into a thermal cycling oven. These ovens vary the temperature of the modules through a predefined temperature cycle. The cycle is repeated a very large number of times. At regular intervals the modules are checked to assess functionality. The modules are exposed to a test temperature cycle far more damaging than the in-service load. Power cycling involves varying the operating power handled by a number of test modules in a manner that varies the module temperature over a wide range.

One of the aims of these methods is to accelerate the module life cycle. The reliability of modules under accelerated testing load profiles is then extrapolated to obtain the in-service life time using ‘acceleration factors’. This reliability assessment methodology enables the module lifetime can be analysed fairly quick. There are however a number of issues with this method. Firstly differing failure mechanisms are dominant under differing temperature cycles so module reliability may differ widely from that predicted. The testing process can be expensive and time consuming, often taking many months to perform. However a more interesting issue also arises – the reliability of ostensibly identical modules subjected to identical loads can vary quite widely. This variation may be a result of minor manufacturing variations – uncertainty – in the design.

5.2 Integrated design optimisation approach

An integrated numerical modelling and design optimisation methodology has been developed to aid development of future PEMs. It is hoped that the methodology will be beneficial in enhancing the design engineer’s understanding of the influence of design parameters upon module reliability and by providing the ability to determine the optimal design within a number of constraints. Additionally, the ability to consider process and material uncertainty and resulting effect on component and system lifetime may improve design and maintenance processes leading to a reduction in the number of in-service failures.

The design process presented in this work is based on Finite Element computer modelling and the response surface optimisation approach. The response surface method is a statistical method that uses data describing the performance of a system at a number of sampling points to form a simple algebraic function able to approximately describe the system. The method was developed initially by Box & Wilson [19] in 1951. The methodology has been further developed by, for example, Zhao et al and Wang et al [20, 21]. In its simplest form, the response surface method fits a polynomial function to a set of data points using a regression approach such as least squares method [22]. If we consider, as a simplistic example, a hypothetical component in which a measure of performance, such as ‘peak stress’, in varies with a design parameter, such as ‘thickness’. The value of peak stress can be determined, either numerically or experimentally, for a number of differing values of component thickness. A polynomial function can be fitted to these data points providing a representation of the variation of peak stress with thickness. Although there is likely to be inaccuracy in both the value of the data points and the polynomial fitting the response surface usually provides a usefully accurate representation. The process is illustrated in Figure 3.

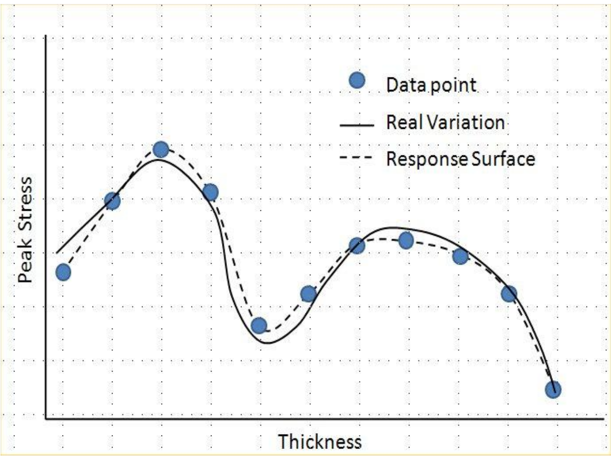

Figure 3: One-dimensional response surface approximation.

The process can readily be extended to N dimensional design hyperspace, with the polynomial function describing a multi-dimensional surface. This process requires a parameterised design – i.e. rather than using pre-defined module geometry, the topology defining the fundamental design is defined. The value of each of the design variables is allocated a permissible range. The definition of a parameterised design and parameter range essentially defines a continuously variable system design, referred to as a design space.

The approach taken in this work uses an optimisation algorithm to numerically assess the performance of a number of permissible designs within the defined design space. The results from the numerical analysis are used to form a multi-dimensional response surface. The response surface can be processed to determine the optimal system design and also to analyse the influence of each of the design parameters. This analysis can lead to an enhanced understanding of system behaviour and to the formation of PEM design rules.

During the manufacturing processes, components are machined to set tolerances. The properties of the raw materials used to form components may also vary. Whilst individual variations may be negligible the compound effects of this variation of design on overall the component reliability may be significant. The variation of response variable due to design parameter uncertainty can be evaluated using a Monte Carlo [23, 24] approach. Uncertainty data can be gathered on parameter variation and represented statistically – such as in the form of a standard deviation. An algorithm such as the Box-Muller transform [25] can be used to generate an immense number of system designs by superimposing randomly selected normally distributed variations onto a pre-defined base design or optimal design. The response surface function can be evaluated for each of these designs and a histogram of response distribution can be formed, which can be used to assess and mitigate failure risk. The overall design optimisation methodology is outlined in Figure 4.

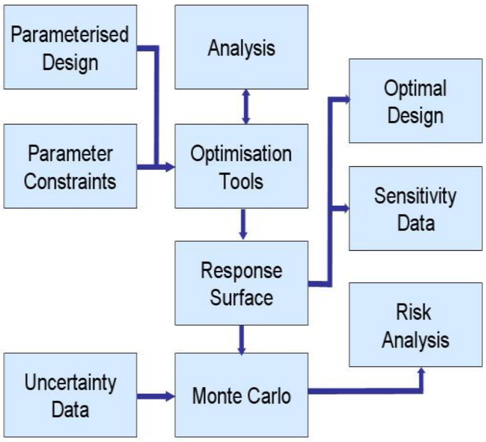

Figure 4: Design methodology flow chart

A number of strategies for optimal placement of the analysis data points can be used. This process is often referred to as design of experiments (DOE) [26, 27]. In a single parameter study it would be simple to place a number of analysis points throughout the parameter range. However as the number of parameters considered in the study increases the number of analysis point rapidly becomes excessive. Factorial designs [28] limit analysis point to the extremes of each of the parameter ranges while composite designs [29] additionally include analysis points at the centre of the parameter range. Advanced methods of DOE formation, such as Latin hypercube [30] and Taguchi [31] methods, could also be utilised.

In this article, a commercial design and optimisation software package Visual DOC [32] has been utilised to generate the design points using DOE methods and to form and analyse the response surface. Alternative optimisation packages such as OPTIMUS [33] and iSIGHT-FD [34] could also be utilised to perform these functions. Numerical analysis has been carried out using the ANSYS multiphysics package [35] although many other software packages capable of performing this function are available. The response variable is essentially a quality metric of the design – in this work the objective has been to minimise the maximum stress in the module although it is intended to develop suitable life-time models to enable the number of thermal cycles before failure to be considered.

In this work, finite element analyses are carried out for the designs generated using the VisualDoc software. The software is then used to approximate the response variable, i.e. the maximum stress in the isolation substrate. With this data, a response surface function can be developed. This function enables an approximate response variable value to be readily determined for a set design of design parameters – without the requirement for further finite element simulations. The relative influence of the design parameters leading on the response can be studied readily using the response equation to enhance the understanding of the design and to form design rules. The capability to evaluate a design almost instantaneously allows methods such as the particle swarm optimisation [36] to be used to determine the optimal module design.

6. Focused Study – PEM Isolation Substrate

6.1 Overview

The design and analysis environment outlined above can be used to analyse a component or group of components within a module. In this article, as an example, a focused study into the design of the isolation substrate has been undertaken. The isolation substrate is made of a ceramic plate covered with a conducting material such as copper on both sides. The conducting layer of the isolation substrate is usually etched to form various patterns. Because of the thermal expansion coefficients are different, stress will develop in the structure and this stress is a function of geometric parameters of the ceramic and the metallization. This stress is the prime drivers for conchoidal fracture and conductor delamination in the substrate. In order to aid the analysis of the effect of design variation on thermally induced stresses in ceramic, a simplified conductor pattern has been defined for this study. The design of the isolation substrate has been parameterised, with a total of 6 geometric parameters have been used. Of these parameters, 5 are related to the copper metallisation and the 6th relates to the substrate itself. The metallisation parameters are edge spacing *S*, conductor width *W*, conductor spacing *S*, conductor corner radius *R* and metallisation thickness T_1. The sixth parameter is the ceramic substrate thickness T_2. The range for each of these parameters is listed in Table I. The dimensions are all stated in mm. Figure 5 and Table I indicate the parameterisation of the test isolation substrate.

Table I: Design parameters and their ranges that define the design space.

	E	R	S	T_1	T_2	W
Maximum	0.250	0.1	0.250	0.250	0.125	1.0
Median	0.875	0.3	0.875	0.625	0.312	3.0
Minimum	1.500	0.5	1.500	1.000	0.500	5.0

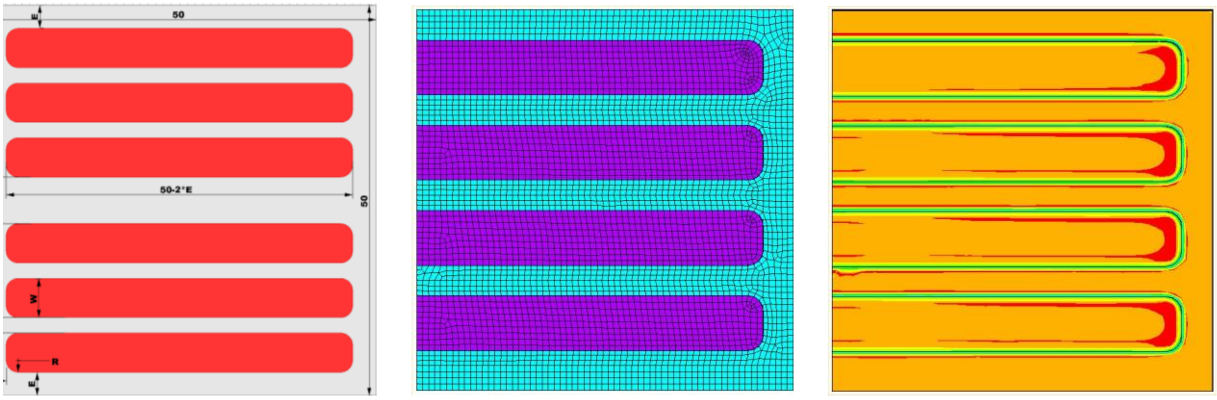

Figure 5: Substrate geometry (Left), FE model of the isolation substrate model (middle) and stress distribution at the top ceramic layer (right).

In order to determine the stresses induced by thermal load a numerical model has been developed. The Finite Element Analysis software package ANSYS [36] has been used to model the deformation of the isolation substrate test coupon. As it is shown in Figure 5, because of the symmetry, only a quarter of the isolation tile structure needs to be modelled. In order to capture the behaviour more accurately in the ceramic close to the interface between the etched copper conductor and the ceramic two layers of shell elements were used for the ceramic layer. The layer close to that interface has a fixed thickness of 0.04mm regardless of the total thickness of the ceramic layer. This layer will be referred to as the top ceramic layer in this paper. Figure 5 shows a typical FEA mesh and the normal stress distribution in the top ceramic layer for a set of design parameters.

Aluminium Nitride (AlN) is a brittle material which exhibits only limited plasticity at very high temperature and therefore it's modelled as an elastic material. Copper, on the other hand is modelled as an elastic-plastic material. Table II indicates material properties used in the simulation. E, ν, α, σ_y, and E_t are the Young's modulus, the Poisson's ratio, the yield stress, the coefficient of thermal expansion (CTE) and hardening modulus respectively. The damage indicator used in this work is the stress but at the bi-material interface the peak stresses are expected to be very mesh-dependent. Therefore, the stress values are volume averaged over each conductor and the results are used as the damage indicator.

Table II: material properties

	E(Gpa)	N	α(ppm/K)	σ_y(MPa)	E_t (MPa)
AlN	310	0.24	5.6		
Cu	103.42	0.3	17	172	425

7. Results

A full factorial DOE with additional central point has been utilised in this study. This design measures the response of every possible combination of parameter minima and maxima. This results in 65 analysis points, each requiring FEA analysis to provide response stress data. The design has been selected due to the ability to provide data points over the entire design space, whilst having minimal number of sample points. The accuracy of the study could be improved by selecting alternative DOE designs with more sample points. For example a Latin hypercube design with k=4 would provide data filling the design space but would require 4096 FEA simulations.

The ANSYS simulations were performed on an AMD Opteron 280 processor workstation, with simulations taking approximately 120 minutes per analysis (run times varied depending upon individual parameter combinations). Total simulation time for the 65 simulations was therefore approximately 130 processor hours.

7.1 Response surface

Second order polynomials with six variables are fitted to each set of the response data obtained in the finite element analysis. For example, for the von Mises stress in the top ceramic layer, the equation is as follows.

$$\sigma_{vm} = c_0 + \sum_{i=1}^{6} c_i x_i + \sum_{j \geq i=1}^{6} c_{ij} x_i x_j$$

where x_i are the design variables and c_i and c_{ij} are constants. For this particular approximate equation, R^2=0.985.

The quality of the data regression can be graphically illustrated in the predicted vs. the modelled results graph as shown in Fig. 6. In this graph the FEA von Mises results and the predicted values based on the fitted response surface equation are compared.

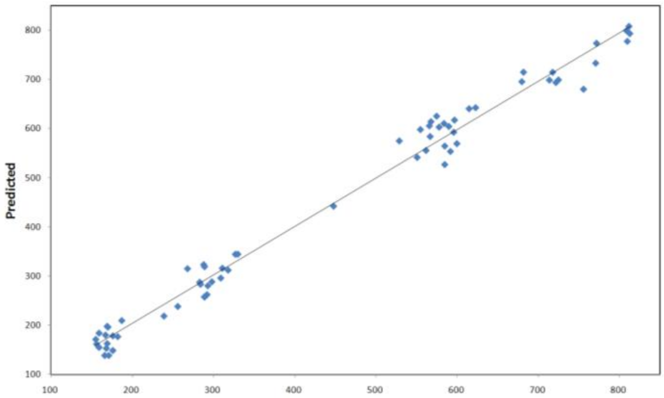

Figure 6: Predicted von Mises maximum stress vs. the response data from the Finite Element Modelling.

7.2 Sensitivity Analysis

In this work six geometrical parameters have been used as design parameters. One of the useful results of this work is the ranking of these parameters in terms of their relative impact on the response variables. This ranking can be made by analyzing the sensitivity of the response variables to the changes in the design parameters. The simplest method is perhaps the use of the magnitudes of the coefficients in the approximate response surface equation. For the von Mises stress, the coefficients of the linear terms in the approximate equation are plotted in Figure 7. This chart shows clearly that the thickness of the metallization on the isolation substrate has the strongest impact on the von Mises value in the substrate and therefore its reliability under cyclic loading conditions. Furthermore, the positive sign of this coefficient indicates that thicker metallization increases stress value and therefore reduce the reliability. The next most important parameter is the thickness of the ceramic layer and a thicker layer helps to lower the maximum stress and increase reliability. The least important parameter is the edge distance. All these discussions are in the context of the design space that has been defined in Table I. In other design spaces the results may be different.

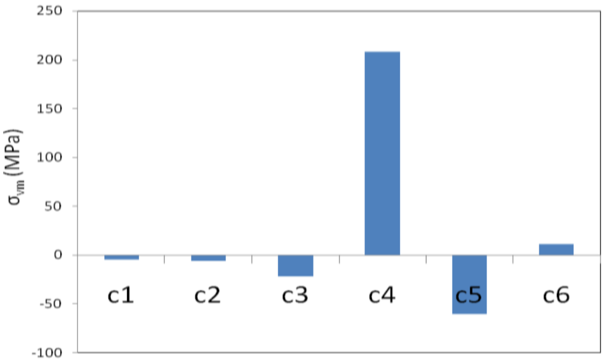

Figure 7: Coefficients of linear terms in the approximate response equation for the von Mises stress σ_{vm}.

7.3 Optimal design

The approximate response surface equation can be used to find the design with highest reliability. The advantage of this method over direct optimization methods is the speed. Because of the approximate equation's simple form, the time it takes for each analysis during the optimization process is negligible.

A gradient based optimization method is used in this work and Figure 8 shows the changes of the objective function, i.e. the von Mises stress and the three most important design variables i.e. the thickness of the metallization, the thickness of the ceramic thickness and the spacing between adjacent metallization. In the optimization process, the objective function changed from 442 MPa to 138MPa, a 70% reduction, from the initial value has been achieved. The normalized design parameters for the optimal design are listed in Table III.

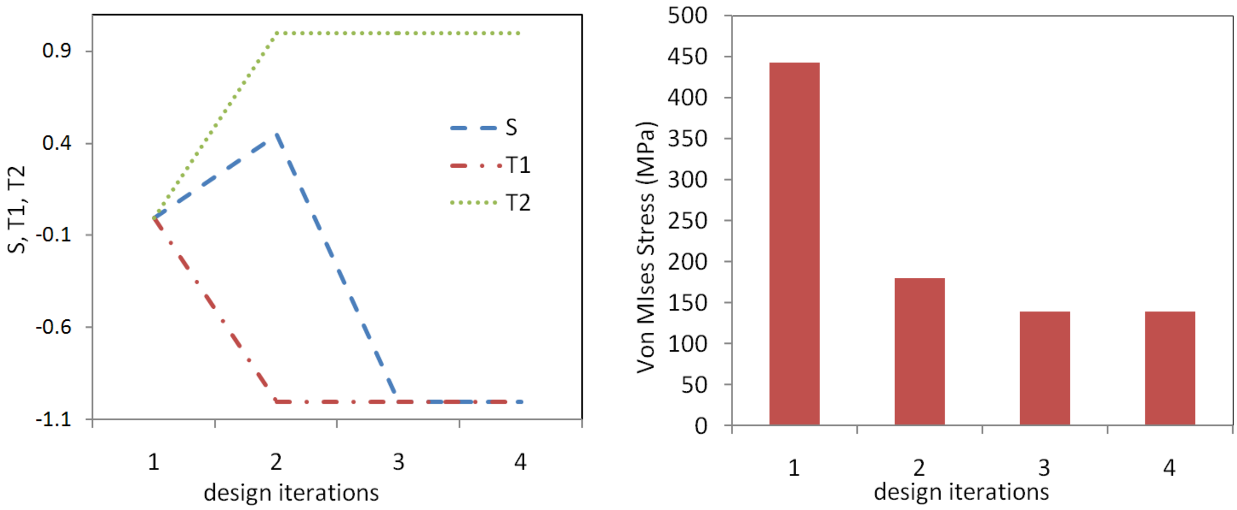

Figure 8: Changes of the design parameters and the objective function during the optimization.

Table III: Optimal design parameters for reliability in normalised design space.

E	R	S	T1	T2	W
-1	1	-1	-1	1	1

7.4 Uncertainty in the design variables and optimization

The existence of the uncertainty in design variables is a fact of life. Because of the input uncertainties the objective function also becomes uncertain and therefore the optimal design obtained using deterministic methods may not be the best design. For example, the optimal design may have a certain probability of violating the constraints and this means that the design actually has a probability of becoming unfeasible.

To illustrate the effect of input uncertainties on the optimization design process, it is assumed that the input variables T1 and T2, i.e. the thicknesses of the metallization and the ceramic are random variables with normal distributions. The mean values and the standard deviations are zero and 0.05 in the normalized coordinate system. The total thickness of the structure, i.e. T1+T2, is required to be between 0.8 and 1.2 mm. An optimization procedure was carried out to minimize the von Mises stress in the ceramic with the added constraint on the total thickness. Figure 9 shows the changes of three design variables and the objective function in the design process. For the optimal design, the metallization thickness could only reach a value of -0.872 because of the constraint on the total thickness and as the result the von Mises stress is 169MPa, 22% higher that the value for the problem without thickness constraint.

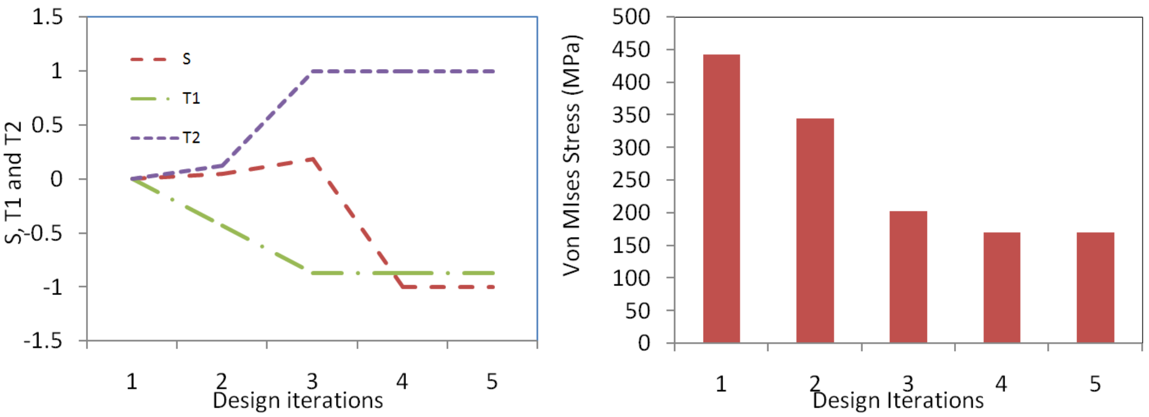

Figure 9: Design variables and the objective function during the optimization process.

Because of the uncertainty of the design variables, it expected that the response functions have a probabilistic distribution around the mean values. For the total thickness, this means that there is a probability that its value violates the constraint. For this ad hoc design problem, the probability of this violation (probability of failure) has been found to be 22%. In order to find a design with an acceptable level of probability of failure, this probability should be used as a constraint in the optimization process. If, for example, the upper limit of the probability of failure is set at 0.1 then an analysis has shown that an optimal design can still be achieved. For the optimal design, the value of T1 and T2 are -0.435 and 0.275 respectively and the von Mises stress is 326 MPa, a decrease of about 26% from the value for the initial design. Clearly, because of the uncertainties and the requirement on the probability of failure the improvement has become much less dramatic than designs that have not taken into account of the uncertainties.

8. Conclusions

A methodology of using optimization software tools for the design of isolation PEM isolation substrates has been developed. DOE and approximate response surface equations have been used to obtain the product design with the highest reliability. Additionally the design process has given insight into the relative importance of design parameters allowing generic design rules to be formulated. For the PEM isolation substrates the thickness of the metallization and the ceramic are the most important design parameters. The effects of uncertainties in the manufacturing process have also been included in the methodology and by using this methodology the risk of the design failure can be controlled or mitigated. This will enable product reliability to be further enhanced. The methodology needs to be further developed to incorporate physics-of-failure models so that the optimal design is linked to the real lifetime of the product. Additional analysis capability needs to be implemented in order to capture thermal management and electrical compliance issues.

9. Acknowledgements

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