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Reliability Analysis for Power Electronics Modules

C. Bailey, T. Tilford, and H. Lu

School of Computing and Mathematical Sciences, University of Greenwich,
Park Row, Greenwich, London, SE10 9LS, United Kingdom.

C.Bailey@gre.ac.uk

***Abstract**: This paper discusses the reliability of Power Electronics Modules. The approach taken combines numerical modeling techniques with experimentation and accelerated testing to identify failure modes and mechanisms for the power module structure and most importantly the root cause of a potential failure. The paper details results for two types of failure (i) wire bond fatigue and (ii) substrate delamination. Finite Element Method modeling techniques have been used to predict the stress distribution within the module structures. A response surface optimisation approach has been employed to enable the optimal design and parameter sensitivity to be determined. The response surface is used by a Monte Carlo method to determine the effects of uncertainty in the design*

1. INTRODUCTION

This paper discusses the reliability of Power Electronics Modules (PEMs). The approach taken combines numerical modeling techniques with experimentation and accelerated testing to identify failure modes and mechanisms for the power model structure and most importantly the root cause of a potential failure. The approach presented has been developed within the UK Government funded project, supported by both the Department of Trade and Industry (Dti) and the Engineering and Physical Sciences Research Council (EPSRC) into the reliability of power electronics modules.

Power Electronics Modules (PEMs) control electrical power. A PEM may perform tasks such as changing phase, voltage, current or frequency of an electrical power source. For example in a system such as a hybrid petrol-electric car the battery cannot be connected directly to the electric drive motors. The DC current from the battery must be modified to an AC supply and regulated in a manner in which the motor power can be controlled by the driver. A power electronics module is used for this purpose. In the case of a hybrid vehicle an IGBT inverter is used to perform this task.

Figure 1 Power Module Applications

PEMs are being used in an increasing large 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. Examples of 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 (fig 1).

With expanding use in critical systems and continuously developing requirements it is crucial to ensure and enhance the reliability of future PEM modules. Incorporation of a design for six sigma

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approach into product design and quality management processes is beneficial to this aim. A strategy to analyse, assess and mitigate against failure and enable a design for six sigma approach to be adopted has been developed to this end.

2. POWER MODULE DESIGN

A power module consists of several layers of insulator such as ceramic, conductor, and semiconductor, some metal wires, encapsulations, metal bars and the casing [1]. Figure 2 (courtesy SEMELAB Ltd.) is a schematic of the module construction.

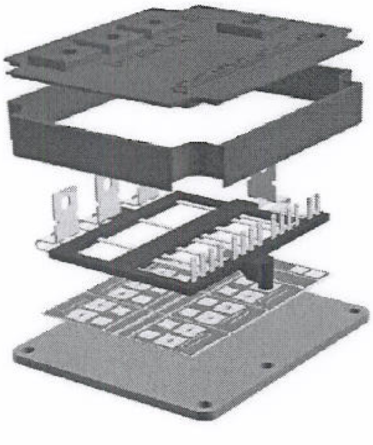

Figure 2 Power Module assembly (Courtesy of Semelab)

A typical 800A IGBT plastic module used in a rail traction application handles almost one Megawatt of electrical power (1200V & 800 Amps). It dissipates about 3KW as heat and is approx. 105mm by 62mm by 30mm in size. A CAD model of a metallised substrate with a semiconductor device linked to a copper track is shown in figure 3.

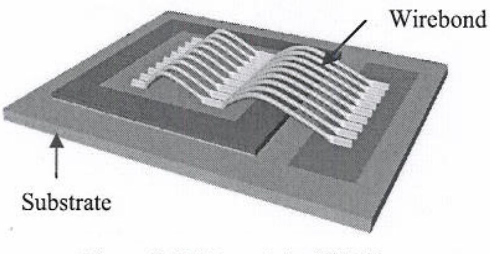

Figure 3 CAD model of PEM geometry

3. RELIABILITY ANALYSIS

3.1. Traditional approaches

A reliability prediction estimates the reliability of the power electronics module as used in the field. This depends on the design of the power module and the in-service environmental conditions it is subjected to during its lifetime. Many power electronics module companies still adopt the MIL-217 [2] reliability prediction methodology to calculate mean time between failures (MTBF). This calculation is based on individual failure rates for each component making up the device which are statistically obtained from field data. It is well documented that this technique can result in very poor predictions. There are other reliability prediction tools similar to MIL-217, such as telcordia [3] and IEE-1413 [4] that are based on historical failure rate data for the parts that make up the module.

3.2. Integrated design optimisations approach

An integrated numerical modelling and design optimisation methodology has been developed to aid development of future PEMs. The methodology was required to provide design engineers with understanding of the influence of design parameters upon module reliability and the ability to determine the optimal design within a number of constraints. Additionally, the need to consider process and material uncertainty was identified.

The design process presented in this work is based on the response surface optimisation approach. The response surface approach attempts to develop a mathematical function relating system response to design parameters. The process requires a parameterised design – i.e. rather than using a pre-defined module geometry, the topology defining the fundamental design is defined. The dimensions of each of the module components are allocated a permissible range. With a parameterised design and parameter range an optimisation package such as OPTIMUS (5) or VisualDOC (6) is able to readily generate new virtual modules with permissible geometric designs. An analysis package such as ANSYS (7) or PHYSICA (8) can be used to determine a response variable for the design. The response variable is essentially a quality metric of the design – in this work the objective has been to minimise stresses 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.

The optimisation package uses a user-defined design of experiments (DOE) [9, 10] method to determine a number of designs to evaluate. The analysis package is used to approximate the response variable. With this data, a response surface function can be developed. This function is enables an approximate response variable value to be readily determined for a set design of design parameters – without the requirement for further numerical simulation. The data obtained can be used to determine the relative influence of the design parameters leading to enhanced understanding of the design and allows design rules to be developed. The capability to evaluate a design almost instantaneously allows methods as particle swarm optimisation [11] to be used to determine the optimal module design.

Process and material uncertainty have been identified as significant issues in PEM reliability. During the manufacturing process components are manufactured to set tolerances. Additionally the material properties of the components may vary. Whilst individual variations are negligible the compound effect of this variation of design variability on overall module reliability may be significant. The variation of response variable due to design parameter uncertainty can be evaluated using a Monte Carlo [12, 13] approach. Uncertainty data can be gathered on parameter variation and represented statistically – often in the form of a standard deviation. An algorithms such as a the Box-Muller transform [14] can be used to generate an immense number of module designs by superimposing randomly selected normally distributed variations onto a pre-defined base design. The response surface function can be evaluated for each of these designs giving a response distribution. This distribution can be used to assess and mitigate against failure risk. The methodology is outlined in Figure 4.

4. FAILURE MECHANISMS IN POWER ELECTRONICS MODULES

The fundamental cause of the majority of PEM failures is thermal cycling. The modules operate at high temperatures and therefore power cycling of the module results in substantial thermal variation. CTE mismatch of the components leads to induced thermal stresses within the module which bring about mechanical failures. A number of significant failure mechanisms affect PEMs. Differing failure mechanisms are dominant in differing operating regimes. This work will concentrate on the two most prevalent failures – substrate fracture and wirebond lift-off.

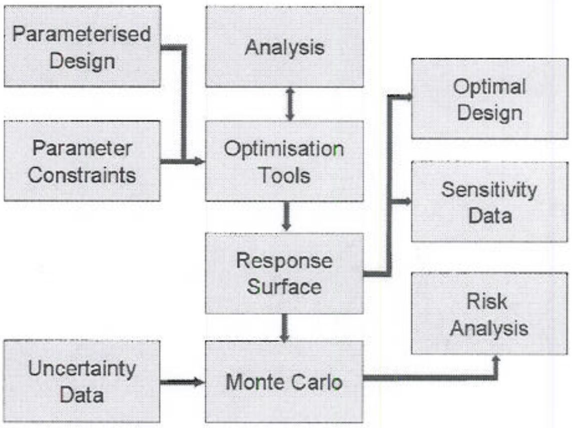

Figure 4 Design methodology flow chart

4.1. Wirebond lift-off

An important reliability issue is wirebond failure. Wire bonding is 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 chip [15]. However, the wire bonds are susceptible to heel crack [16] failures arising from flexing due to thermal expansion or overworked bond heel during ultrasonic bonding [17]. 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. This failure mode is aggravated by wide thermal cycling ranges. In order to determine the most influential design parameters finite element analysis (FEA) models were developed using the nonlinear FEA software package ANSYS. The 3D model (figs 6 and 7) contains a slice of the device along the wire and periodic boundary conditions are assumed. To reduce the model size further, the mirror plane symmetry of the structure is exploited so that only half of the wire and the surrounding structure is included in the model The models has been integrated with optimisation software to enable the design methodology described above to be implemented. Work on evaluating the optimal design is in progress

4.2. Substrate Fracture

Of all the components in a power module, the alumina or AlN isolation substrates and the bonded copper conductor layer are the basic structures on which all other components are built on. The delamination of the copper tracks is an important reliability issue [18] whereas the solder interconnect of the chip mount-down is one of the major failure mechanisms [19]. Therefore the reliability of these two structures of the power module is fundamental to the reliability of the whole module and has duely attracted many research interests [20, 21, 22, 23].

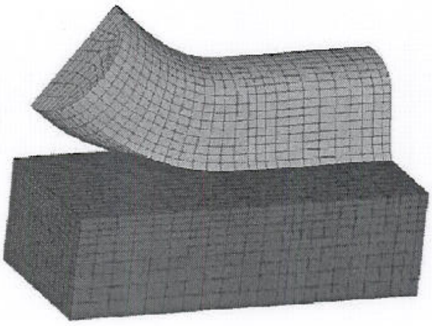

Figure 6 FEA Geometry of wirebond heel

In order to reduce stresses within the substrate a number of dimples are etched into the metallisation in an attempt to decrease stress through increased compliability. This approach is often highly successful in increasing module reliability. In order to assess to impact of substrate dimpling a number of FEA models were developed using the ANSYS package. Initial models were built of a 3 dimensional section of substrate. A number of designs were considered and the stresses induced by thermal loading were investigated. The effect of the dimples was found to be significant. Consider to designs with differing dimple depths – design 'a' with a shallow dimple and design 'b' with a deeper dimple. The FEA solutions show design 'a' has a maximum σ_Z stress of 95 MPa (Fig 8), whilst design 'b' had a maximum σ_Z stress of 76 MPa (Fig 9).

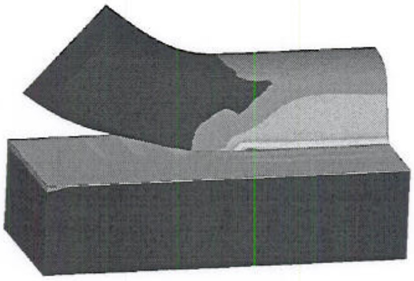

Figure 7 FEA wirebond stress solution

To investigate the ideal dimple arrangement a slice model was developed enabling the design to be analysed using the design optimisation methodology. The slice geometry is outlined in figures 9 and 10. The geometry utilises periodic boundary conditions to reduce problem size. The substrate consists of a layer of aluminium nitride with two layers of copper metallisation. A number of geometric parameters and material properties are considered invariant – see tables 1 and 2. A total of 15 simulations were required to develop an accurate response surface. The relative influence of the design variables (table 3) is listed in table 4. This shows that the combination of radius (R) and indent (I) is the dominant design parameter. A Particle swarm optimisation approach can be taken to determine the optimal design. A Monte-Carlo simulation of 10,000 designs was performed with each variable given an uncertainty standard deviation of 0.5%. This approach would not be feasible if a full FEA analysis were required for each of the designs. The resulting distribution (fig 12) can be used to determine the proportion of samples with a response value in excess of a critical stress value. If a valid physics-of-failure model were implemented the design engineer could make an accurate assessment of the proportion of modules which could not withstand a pre-defined number of thermal cycles. This information can be used by the design engineer to improve the design and reliability of future power electronics modules.

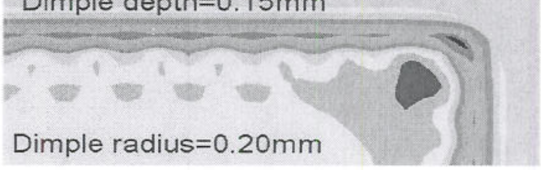

Figure 8 Dimple design 'a'

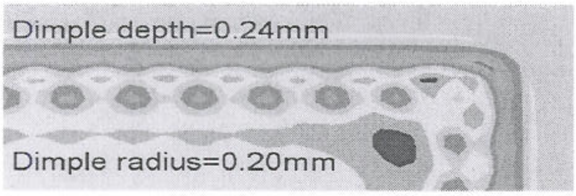

Figure 9 Dimple design 'b'.

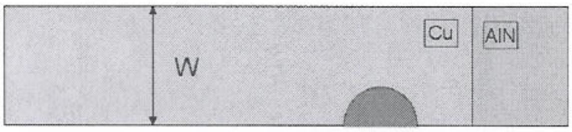

Figure 10 FEA geometry top view

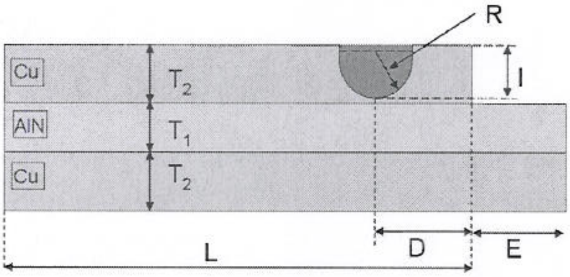

Figure 11 FEA geometry side view

Parameter	Symbol	Value
AlN Thickness	T1	0.25 mm
Cu Thickness	T2	0.30 mm
Length	L	2.5 mm
Etch	E	0.5 mm

Table 1: Fixed geometric parameters

Material	AlN	Cu
E (GPa.)	310	103.42
v	0.24	0.3
α(ppm/K)	5.6	17
σ_y(MPa)	-	172
ε (MPa)	-	425

Table 2: Fixed material properties

Parameter	Symbol	Max	Min
Radius	R	0.5 mm	2.75 mm
Indent	I	0.5 mm	2.75 mm
Edge Spacing	D	1.0 mm	3.0 mm
Spacing	W	1.0 mm	3.0 mm

Table 3: Design variables

Variable	Relative influence
Spacing	0.000
Edge Spacing	0.000
Radius	0.000
Indent	0.000
Spacing * Edge Spacing	0.004
Spacing * Radius	-0.090
Spacing * Indent	-0.062
Edge Spacing * Radius	-0.089
Edge Spacing * Indent	-0.024
Radius * Indent	1.000
Spacing * Spacing	0.009
Edge Spacing * Edge Spacing	0.004
Radius * Radius	-0.034
Indent * Indent	-0.470

Table 4: Relative Influence

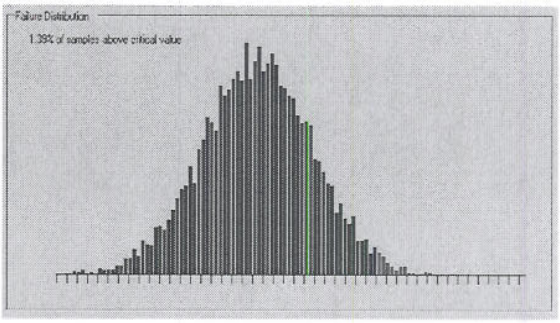

Figure 12 Response distribution.

5. CONCLUSIONS

The main failure modes of power electronics modules have been assessed and modelled. These models can be used in an integrated design and optimization methodology to determine the optimal design for a module. Uncertainty information can be incorporated into the process to produce a response distribution. This information can be used by manufacturers to assess and mitigate against risk, and enables a design for six sigma approach to be adopted.

6. ACKNOWLEDGMENTS

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