RELIABILITY STUDY OF POWER MODULE BY STOCHASTIC UNCERTAINTY METHOD FOR AN AERONAUTICAL APPLICATION

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Keywords: *Reliability, IGBT module, Thermal cycling, Solder ageing*

Abstract

This work studies the reliability of power electronic component in aeronautical environment to the ageing effect of the thermal cycling. The structure fatigue is sensitive to the process assembly conditions especially of the soldering process. To put in evidence this fact we used the methodologies based on the mechanical stochastic uncertainty method to take into account the random parameters by the Finite Element simulation. After study analysis of the Darveaux failure function by experimental thermal cycling, we exposed the result on the IGBT module of the reliability function, especially on the Parameter elasticity to define the process rule to high reliability structure. In addition, we propose an alternative to the usual Weibull distribution to represent the failure probability density function of the fatigue base plate solder of IGBT module by the Birnbaum-Saunders distribution.

1 Introduction

Today the aircraft industry needs to optimize the power need as to reduce consumption. To reach this objective we need to reduce the aircraft weight and to optimize the power sources. The "More Electrical Aircraft" is an answer by enabling a simplification of the hydraulic and pneumatic circuit system, this is only a first step before reaching their total suppression. The power demand will also be optimized as electrical actuators have a better global efficiency, and in the same way the removing of the hydraulic pipes simplifies maintenance. However the first concerns of the aircraft industry is the reliability of their system for security and maintenance reasons.

The power components, as IGBT module, are identified as the weak point and its reliability strongly determines the system reliability. The robustness of the IGBT module for an aeronautic application, in comparison to other application fields, is a real quest due to high temperature variation, moisture and cosmic ray phenomena [1], especially for harsh environment like nacelle motor.

Whereas, a constant failure rate for the standard electronic components can be defined, the IGBT modules, such as solders, are submitted to an ageing effect as of their startup fatigue law based on the Finite Element (FE) Method like Coffin-Manson or Morrow of solder alloys in order to predict failure event [2].

However these methods do not make it possible to take into account the distribution of parameters that depends on the assembly process and that are really determining for the module reliability.

This work deals with the failure probabilistic prediction of IGBT module based on the base plate solder delamination criteria employing a structural reliability method. First, we described the probabilistic coupling methods to compute the failure probability and the Finite Element model of the IGBT module and the boundaries conditions. After that, we estimated the coefficient life fatigue prediction from experimental ageing tests and the random variable.

And finally the result permits to estimate the elasticity of each random variable, and the reliability of the structure for a given failure criteria.

2 The probabilistic method

The probabilistic structural approach consists in determining the probability of failure of a given system [3]. In this case the input data of traditional Finite Element method are not considered constant but as an uncertainty random variable defined by a statistic distribution. All relevant uncertainties influencing the probability of failure are then introduced in the vector *X* of basic random variables. In addition, the failure of the system is modelled by a functional relation *G(X)* called limited state function (equation 1) and is defined null or negative on the failure domain.

$$G(\{X\}) \le 0, \forall X \in failure \cdot domain \qquad (1)$$

Components x_i of the vector *X* is one realization of basic random variables. It's then possible to define the probability of failure for the system as the equation 2.

$$P_f = \int_{G(\{X\}) \le 0} f_{\{\mathrm{X}\}}(\{\mathrm{x}\})\mathrm{dx}_1 ... \mathrm{dx}_\mathrm{n} \qquad (2)$$

The problem to solve this multi-dimensional integral comes from the fact that the limit state function is not explicit, because its evaluation is the result of FE call. Approximation method can be established to compute the multi-dimensional integrate of the equation 2 by substituting the limit state function with a linear or second order hyper plane called respectively First Order and Second Order Reliability Method (FORM or SORM) (Fig. 1).

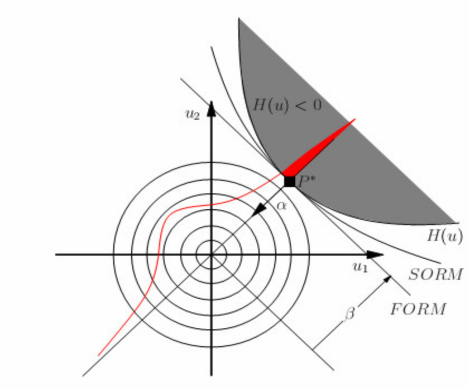

Fig. 1 Approximation methods FORM/SORM

A solution to solve equation 2 consists in finding an explicit function or method that can approximate the finit element output: the Response Surface (RS) method is proposed. A numeric Design Of the Experiment (DOE) is made for constructing the equivalent surface. The DOE is constructed in the standard space and described in [4].

3 Finite element modeling

3.1 FE element model geometry

The structure modelized is simplified to a multilayer assembly: the ceramic substrate metallized brazed by a soft solder on the base plate. The other elements of the assembly are not integrated because they do not participate to the final result of the mechanical stress.

The numeric model is done on ABAQUS 6.6-1, (Fig. 2) is simplified to the quarter of structure to limit the number of nodes for calculus time reason. The nodes are quadratics of C3D4 type to be in accordance to the materials models used.

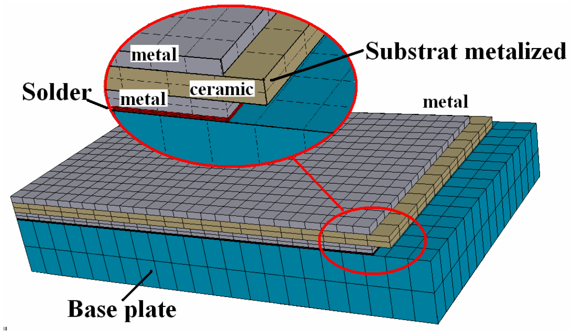

Fig. 2 IGBT module 3D FE model

3.2 Materials properties

The main material properties used on the FE model are described on the Tab. 1. The ceramic substrate and the base plate materials are modelized by an elastic linear behavior. The metallization material is modelized by an elastic-plastic model to take into account the observed hardening effect.

Material	Young Modulus	Poisson Coefficient	Elastic limit	Tangent modulus
Solder	34.5 GPa	0.4	Anand	
Metallization	70.6 GPa	0.34	17.8 MPa	350 MPa
Ceramic	335 GPa	0.25	Elastic linear	
Base plate	192 GPa	0.24	Elastic linear	

Tab. 1 Principals materials characteristics

The soft solder is modelized by a viscoplastic constitutive model, the Anand model [5].

In this model the plasticity and creep are unified and described by the same set of flow and evolutionary relations, it is applied to represent the inelastic deformation behavior for solder alloys. The Anand model gives a more complete description of the deformation behavior of the material. The creep comportment is modelized by the equation 3.

$$\varepsilon_{cr} = A.\left[\sinh\left(\frac{\xi\sigma}{s}\right)\right]^{\frac{1}{m}}.\exp\left(\frac{H_0}{R.T}\right) \qquad (3)$$

where H_0 is the activation energy, ξ the stress multiplier, s the saturation value and m the strain rate sensitivity of stress.

3.3/ Thermal cycling loading

The thermal cycling introduced on the model is composed in two phases, the assembly phase and ageing process phase.

The first step (Fig. 3) represents the thermal profile of the soldering process necessary to assemble the base plate to the substrate-metallized by the soft solder and the storage step after the assembly. This profile is introduced to simulate the residual stress remaining in the structure after the assembly and the relaxation of the solder by the creep phenomena.

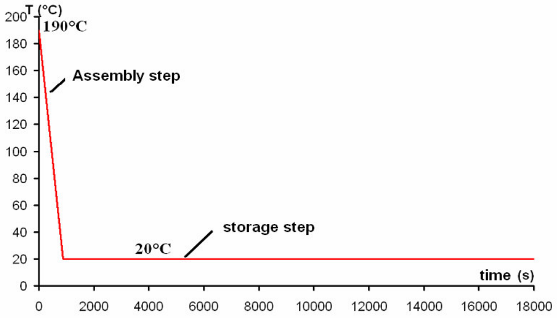

Fig. 3 Process temperature profile

The second loading step (Fig. 4) represents the accelerated thermal cycling done on the IGBT module. This profile represents two thermal cycles applied on the structure; it represents a thermal air-air choc from -55°C to + 125°C. This profile is similar to the experimental measure done during the ageing experimentation of the component.

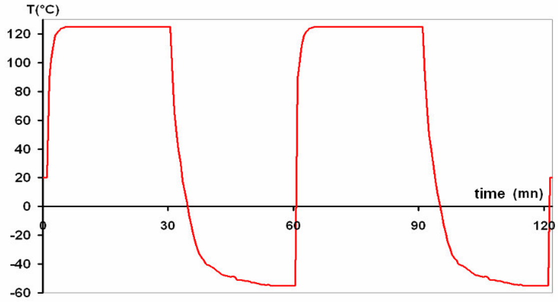

Fig. 4 Accelerated ageing thermal profile

4 Failure mode evaluation

4.1/ Life prediction model

The Darveaux's model represented by the equation 4 is the most popular, among all energy based methods [6]. Its expression is composed of two terms. The first represents the energy necessary to initiate the crack on the solder, the second one represents the crack propagation due to the energy dissipated by cycle. The failure criteria is fixed for a crack length (a) reached after N_f cycles.

$$N_{f_{calc}} = A_1 \Delta W^{K_1} + \frac{a}{A_2} \Delta W^{-k_2} \qquad (4)$$

The A_1, k_1, A_2 and k_2 are the fatigue coefficient material dependent parameters. The coefficient evaluation needs experimental ageing test. The models permit to evaluate the fatigue life of solder joints from the density energy dissipated per cycle.

From our study we take the inelastic strain based on a model that considers plastic and creep phenomenon due to the CTE mismatch. The energy density is evaluated from the average on all the volume from the equation 5.

$$\Delta W_{in} = \frac{\Sigma_e \Delta W_{in_e} V_e}{V_{tot}} \qquad (5)$$

4.2/ Experimental test

To estimate the Darveaux parameters we realized 2000 accelerated thermal cycles (-55°C, + 125°C) on ten IGBT modules from different manufacturing batches. The acoustic scan non destructive analysis permits to observe the crack initiation of the solder and the delamination progress.

After thermal cycling we realized destructive microsection anlysis (Fig. 5) to confirm the localization in the solder of the crack observed. These analyses show a variation of the solder thickness due to the process soldering condition.

The experimental result permits to define the crack length in function of the thermal cycle (Fig. 6). We correlate these results with a numeric approach to determine the energy dissipated by cycle. The observation shows a constant propagation versus time [7].

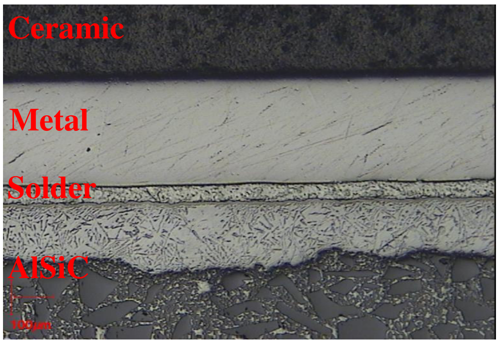

Fig. 5 Microsection of the IGBT module

Although the crack propagation changes the geometry solder we suppose than the dissipated energy ageing is constant in time.

The energy dissipated, calculus by EF simulation, permits the estimation of the Darveaux coefficients (Tab. 2).

A_1	k_1,	A_2	k_2
25 198	- 0,96	0,76 10^{-7}	-2,28

Tab. 2 Darveaux's coefficients soft solder

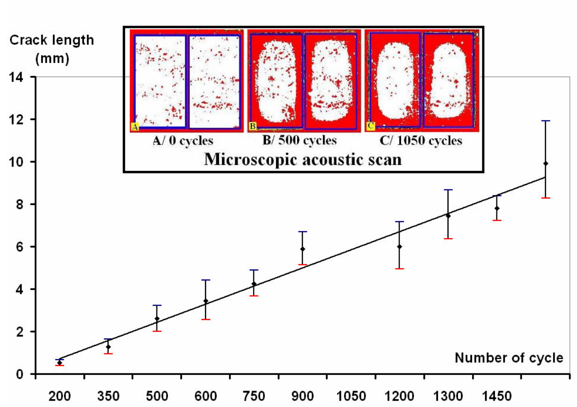

Fig. 6 Solder crack length propagation for a 20µm solder thickness

5. Simulation results

5.1 Random variable and limit state function

From the mechanical failure, we consider as random four variables defined with their density function. The first variable is the thickness *e* of the solder to take into account the process variation. The other variable takes into account the creep solder material variation due to the thermal cooling profile process. The parameters are H_0, the *m* exponent and ξ. The parameters distribution type and value are listed in Tab. 3.

Random variables	Distribution	Mean	Standard deviation
E	Log-normal	0.15	0.03
H_0	Normal	4121.31	800.0
M	Normal	0.303	0.05
Ξ	Normal	11.0	2.0

Tab. 3. Variable and law type

The limit state function, relating the thermo-mechanical fatigue of the solder, is written to consider that the system falls into the failure field if the number of cycle does not reach a target value (equation 6).

$$G(X) = N_{f_{calc}} - N_{f_{target}} \qquad (6)$$

$N_{f_{calc}}$ and $N_{f_{target}}$ are respectively the number of cycle before failure computed by the finite element code according to equation 4 and the objective number of cycle that the system must reach. The limit crack propagation accepted (a) is 3mm in accordance with the thermal simulation and experimentation [8].

5.2/ Results on FE input random variables.

A response surface is built to approximate the inelastic energy during one cycle. The variance analysis for various shapes of function is fitted with least square algorithm. Linear and quadratic functions are investigated and show the necessity to take a quadratic formulation to achieve an accurate solution.

The correlation coefficient R², near from 0.94, confirms the good fitting of the Surface Response Model (RSM) according to the FE model results. The Fig. 7 shows the results of the fitting procedure.

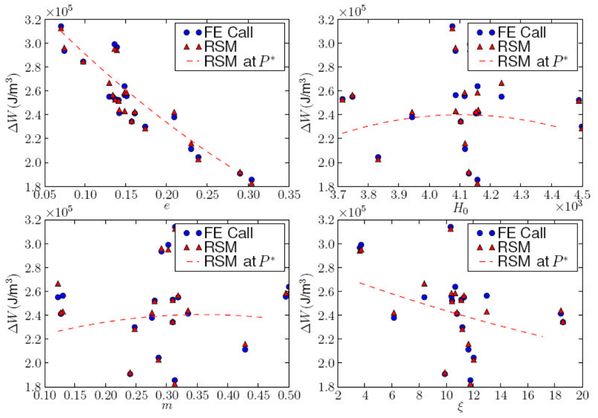

Fig. 7 Design of FE experiments and RSM.

With this response surface, a FORM analysis is made. The results of sensibilities give us indication about the influence of the random variables (variation of the probability of failure compared to the variation of the random variable parameters). The results of mean elasticities in Fig. 8 demonstrate the importance of the thickness value of the solder in comparison with the random parameter solder materials importance. This result is correlated by the sensitive study on the standard deviation on the Fig. 9. The scatter of solder thickness has a more important impact than the variation of the solder random variable.

Those results give process optimization indication to increase the reliability of the assembly.

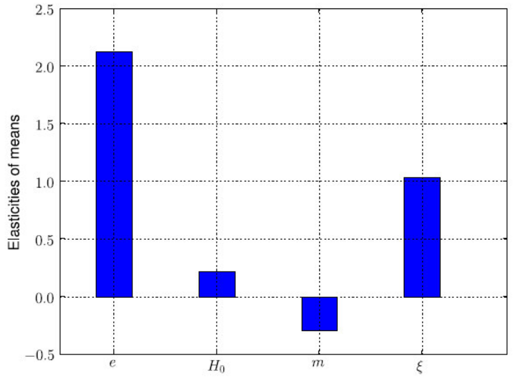

Fig. 8 Means elasticity's with respect of random variable.

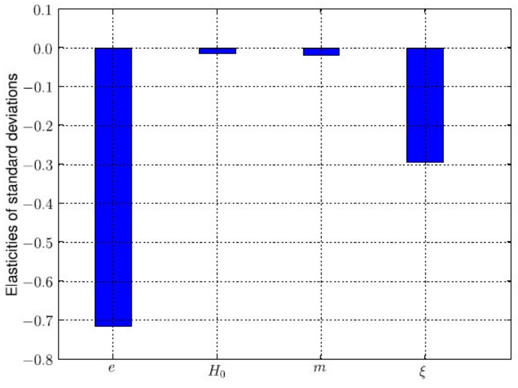

Fig. 9 Standard deviations elasticity's with respect of random variable.

The results show two approaches, the sensibility of mean that permits to choose the best design value. The sensibility of standard variation that permits to define the critical process steps to minimize the scatter of the variable to increase the reliability.

5.3/ Result on the reliability of the structure

With the explicit formulation of inelastic energy dissipated during one cycle, we estimated the probability density of the number of cycle at failure for the structure. We sample 100 000 Monte-Carlo simulations with respect of density of the input random variables and with fatigue life function defined with a 3mm crack length fig. 10.

The given density can be fitted on common density function. We fit here the number of cycle at failure with the well-know Weibull distribution (equation 7). and Birnbraum-Saunders distribution (equation 8) used to model failure times due to a crack failure [9].

$$f(x,k,\lambda,\theta)=\frac{k}{\lambda}\left(\frac{x-\theta}{\lambda}\right)^{k-1}e^{-\left(\frac{x-\theta}{\lambda}\right)^{k}},x>\theta,k,\lambda>0 \qquad (7)$$

where k, λ and θ are respectively, the shape, the scale and the location parameters.

$$f(x)=\frac{\sqrt{\frac{x-\mu}{\beta}}+\sqrt{\frac{\beta}{x-\mu}}}{2\gamma(x-\mu)}\phi\left(\frac{\sqrt{\frac{x-\mu}{\beta}}-\sqrt{\frac{\beta}{x-\mu}}}{\gamma}\right)x>\mu;\gamma,\beta>0 \qquad (8)$$

where γ, β and μ are respectively, the shape, the scale and the location parameters.

For fitting the distribution parameters, we use here two statistical methods. The Least Square (LS) method (equation 9) consists in minimizing the error between the model and observations.

$$\hat{\theta}=\arg\min\sum_{n}\left(f(x_i,\theta)-y_i\right)^2 \qquad (9)$$

where $f(x_i,\theta)$ represents the density function depending on the unknown θ parameters and y_i the normalized observed count in the i^{th} of the k bins.

The second method (equation 10) used here is the Maximum Log-likelihood Estimation (MLE) which consists in maximizing the likelihood function [10].

$$\hat{\theta}=\arg\max\sum_{n}\log\left(f(x_i,\theta)\right) \qquad (10)$$

The Weibull's parameters fitting by LS and MLE methods and Birnbaum-Saunders parameters are respectively given in the Tab. 4 and Tab. 5.

Method	k	λ	θ
LS	1.9498	3178	8327
MLE	2.5328	4492	7275

Tab. 4 Weibull model parameters

Method	γ	β	μ
LS	0.3745	4612	6384

Tab. 5 Birnbaum-Sanders model parameters

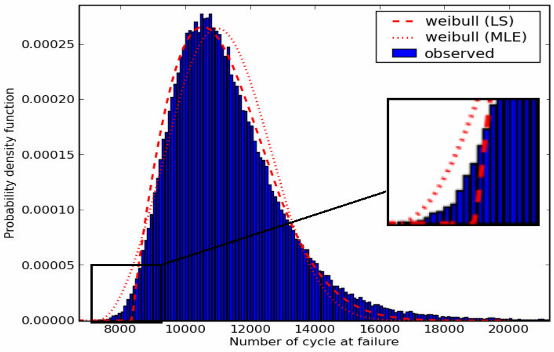

Fig. 10 Probability density function of number of cycle at failure estimated by Monte-Carlo samples and Weibull model from LS and MLE fitting.

The results show (Fig. 10) in a first time, that the LS method under-estimates the behavior in the appearance of the first failure whereas the MLE has a best behavior for this last even if this method is pessimist. It returns a beta parameter that is more relevant for fatigue failure with MLE. The Birnbaum-Saunders model (Fig. 11) is more relevant for the whole behavior than Weibull model especially for the beginning (important because of probability compute with FORM formulation) and the end of the density curve.

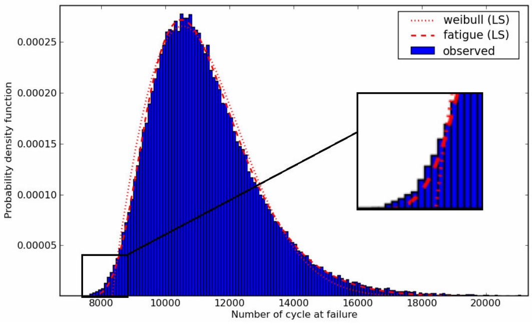

Fig. 11 Probability density function of number of cycle at failure estimated by Monte-Carlo samples and Birnbaum-Saunders and Weibull model.

The failure cumulative distribution Fig. 12 permits to define the 5% life time of the structure at 8 600 thermal cycling. This result is pertinent, because the delamination phenomena for 150µm solder thickness is experimentally very slow (less than 800 µm for 2000 cycles). However the failure probability "Reliability" of the structure to reach 2000 thermal cycling without failure is under 1 FIT, this is in accordance with the result estimated. We can conclude that the IGBT module failures, due to ageing effect on base plate solder, will not disturbed the electronic component reliability.

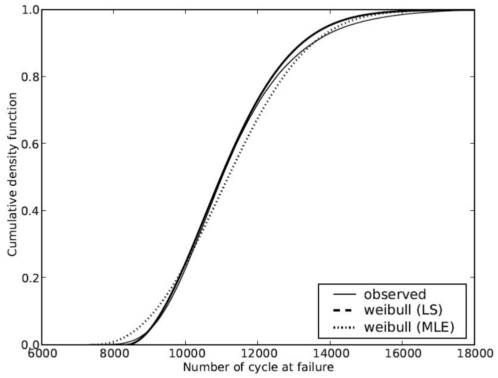

Fig. 12 Failure cumulative distribution function of the assembly.

5. Conclusion & perspectives

The structural reliability method permits to estimate the life time of the IGBT module for one critical failure risk. This method needs to be able to define the random data parameter of the IGBT module structure (material properties, geometry ...) due to the manufacturing process. We could define not only the design parameters to reach high reliability, but also introduce the critical process step, which is one of the reliability key of power component. In this study we demonstrate that 2000 thermal cycles for a 150µm solder do not affect the reliability of the component. These results demonstrate than the delamination solder base plate phenomena should not reduce the electronic component reliability.

Today this methodology permits us to give the variability criteria from the geometry of a structure or from a material behavior to reach a reliability objective at the first design of the structure. This permits also to define the process and its authorized variation.

In perspective of this work we will introduce the random variables Darveaux fatigue law to estimate their sensibilities.

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