MECHANICAL BEHAVIOR AND DAMAGE OF TRIDIMENSIONAL MULTILAYEREDCERAMICS-TUNGSTEN POWER ELECTRONIC SUBSTRATES

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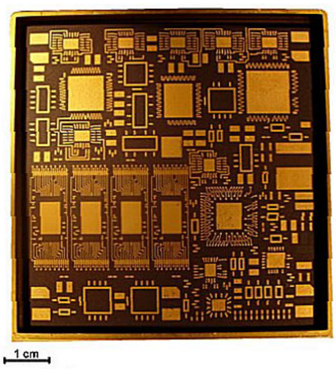
AbstractPower Electronic High Temperature Co-fired Ceramics (HTCC)substrates use metal as electrical and thermal conductor. The electrical insulation is achieved by insertion of ceramics layers. This study is devoted to the analyses of damage mechanisms of tungsten-alumina co-fired 3D subtrates. The most innovative feature of these substrates is the three dimensional nature of the electrics lines circuit. This circuit has to be small enough to connect a lot of compounds (few millimetres in width). Most important, it has to be designed to operate under large thermal loading amplitude.The main problem encountered stems from the heterogeneity of the structure. As a matter of fact, alumina is a poor thermal conductor and has a low expansion coefficient, while tungsten lines have higher expansion coefficient and capability of thermal conduction. Since both materials are co-fired to form the 3D structure, thermal internal stresses arise because of ambient temperature variations and thermal dissipation in operating conditions due to the Joule effect. In addition, the complexity of the geometry is at the origin of stress and strain singularities, in particular at the material interfaces. Residual stresses stemming from the orientation given to the alumina foils by the pouring process were determined using fracture experiments. These residual stresses change abruptly at the interface between two layers of ceramics within the substrate and hence may contribute to the fatigue damage of the circuit lines.Two types of fracture are hence observed in such substrates, a brittle fracture of the ceramics and an interfacial progressive delamination. Both of them require cyclic loading of the compound.
The first type of fracture is modelled by a Weibull law, which has the advantage of accounting for gradient and scale effects. The failure probability of the ceramics layer is function of the stress distribution in the brittle material that evolves because of thermal loads and of the non-linear behaviour of the metal lines.
Modelling requires identifying the mechanical behaviour of each material as a function of the temperature at the suitable scale, i.e. a hundred microns scale. Some special samples have been made to characterize alumina.

1 INTRODUCTION

Improving the reliability and the fatigue life of power electronic substrates is a real challenge. The aim of this research is to predict the fatigue behaviour of an aluminaHTCC (High TemperatureCofired Ceramic) substrate.Cofired ceramic substrate (HTCC) is a multi-layered structure that contains 3D tungsten circuit lines. The metallic circuit lines are printed on the ceramic layers before their assembly. Conductive *vias* pierce the layers and are filled with metal to form electrical interconnections between circuits. The pileup (ceramic and metallisation)is sintered at high temperature to form a monolithic structure with a three dimensional wiring system.



(a)

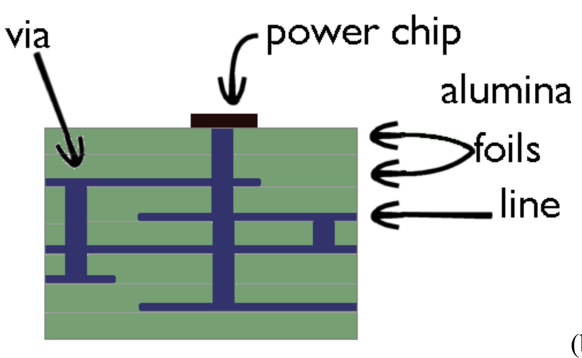


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Figure 1. (a) HTCC package (hermetic multi-chic module) processed by the company Egide, (b) Schematics of the multilayered structure.

In operating conditions, two types of fatigue cycles are experienced by HTCC substrates. The first type, labelled as active cycles, stems from the non-uniform heating of the substrate in operating conditionsbecause ofthe heatproduction by the active parts of the module (chips) and the Joule's effect in the circuit line. The second type, labelled as passive cycles, stems from ambient temperature variations (that can range from -55 °C up to 200 °C in extreme environment, e.g. avionics for example). These thermal cycles cause thermal fatigue for two main reasons:

- First, the alumina foils and the tungsten lines display different thermal expansions. Because the HTCC substrate is a monolithic structure, elastic strains, and hence stresses, riseinside the substrate to accommodate the difference between the thermal expansions of both materials when an ambient temperature variation is experienced by the substrate.
- Second, the heat production by power chips is at the origin of local temperature growth at the chip/substrate interface. The low thermal conductivity of the substrate promotes temperature, thermal expansion and hence stress and strain gradient through the substrate.

The thermal fatigue failure of a DBC substrate was the object of previous researches [1-6]. Two main failure mechanisms were identified and modelled [1-5], first a brittle fracture of the ceramics due to bulk stresses inside the substrate, second a progressive delamination at the metal/ceramic interface by fatigue crack growth. In DBC or HTCC substrates, the ceramic layers display a linear elastic behaviour while the metallic parts are elastic-plastic [8]. Though the ceramic is linear elastic, the stress amplitude within ceramic parts can evolve during fatigue cycling because of the non-linear behaviour of the metallic lines. A 3D finite element model of the HTCC substrate was built to analyse this problem and determine the fatigue resistance of the substrate.

However, individual material characteristics had first to be collected to feed this FE model. For this purpose, the analysis of the failure resistance of the ceramic layers was first determined.

The brittle fracture of the ceramic is a probabilistic event related to the probability of presence of micro-defects in the volume of material tested. The Weibull's law can be used to model the failure probability of the ceramic [8]. In the present case, small scale experiments were conducted, because of the small thickness of the ceramic layers and the small scale of the stress fields induced by the temperature gradients below the power chips or by the stress concentration associated with *via*.

In addition, the processing of the HTCC substrate is expected to be at the origin of residual stresses inside the substrate that superimpose with thermal fatigue stresses. Tests were thus conducted to determine the Weibull's coefficients of the ceramics and the internal stress level inside the substrate inherited from the process.

2 PROCESSING AND DESIGN

"Raw" ceramic is obtained from alumina powder (90%) and organic components which, when mixed,form a paste ("barbotine"). This paste ispoured to obtain a foil (with a thickness that ranges between 100 and 700 micrometers), which is then driedto evaporate the solvents.

The foils are cut and pierced to create the vias (around 100 micrometers in diameter) and the locating holes required for a precise assembly of the layers used to build the substrate. Holes of complex shape (rectangles or squares with rounded corners) are also cut in the foils in order, for example, to install a chip at mid-thickness of the substrate.

Metallic inks are used for printing thecircuit lines (around 10 micrometers thick, 100 micrometers wide)on each ceramic layer and for filling up via holes in order to establish the conduction from one layer to another. The inks are obtained from tungsten powder (90%) and solvents.

Ceramics layers arethen stacked so that the pouring direction of each foilis at 90° from the next one. This arrangement is required to avoid a deformation of the substrate during the final heat treatments used to produce a solid monolithic structure. It is expected that the absence of deformation is associated with the existence of residual stresses inside the pileup that are aimed at being determined in this analysis. Finally the substrate is subjected to a co-firing heat treatment at high temperature (1600°C) and within ahydrogen atmosphere.

The holes (empty of filled with tungsten) act as stress concentrators and can be at the origin of the brittle fracture of the ceramic or of the delamination of the circuit lines during fatigue cycling. A thermo-mechanical analysis of this problem is therefore required to propose safe design rules for those substrates.

3 TESTS AND CHARACTERISATION

The material data required to perform such analyses are as follows :

- Thermal expansion of alumina (rolling and transverse direction) and of tungsten ;
- Elastic constants of both materials ;
- Elastic-plastic behaviour of tungsten lines and vias ;
- Failure criteria for both material before and after fatigue cycling

The present paper is devoted to the determination of the failure probability function of the alumina and the determination of internal stresses inherited from the assembly process.

3.1 Three points bending tests

Three point bending tests were first conducted to determine the fracture resistance of the alumina. Two types of specimen were used, type 1,with a width w_1=5mm and type 2, with a width w_2=2.5mm. In both cases, the thickness was about t=200µm and the distance between two supports is$L$=30mm. The thickness was measured before each tests, since t varies by up to 30µm around the mean thickness t=200µm. The specimens were all cut from a stack of two foils ofalumina with their pouring direction at 90°toeach other.

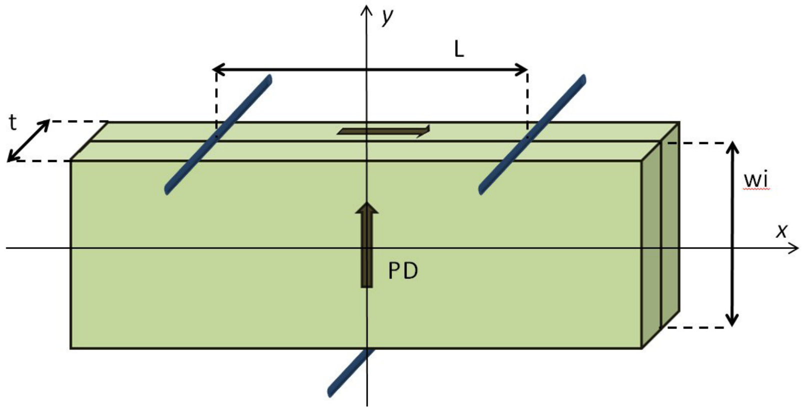


Figure 2.Schematics of the three points bending test. The dark arrows indicate the pouring directionof each foil.

A loading ramp was applied on each specimen and the failure load $F$was recorded. The Weibull's stress $\sigma_W$was then determined for each broken specimen. For this purpose, the stress distribution within the specimen is calculated and the failure probability in each sub-volume dV is determined so as to calculate the failure probability of the specimen using the weakest link hypothesis. The stress field inside the specimen is as follows:

$$\sigma_{xx} = \sigma_b \left|\frac{L-2x}{2}\right| \frac{2y}{w_i} \quad \text{with} \quad \sigma_b = \frac{3}{2}\frac{F}{w_i{}^2} \tag{1}$$

Where F is the load applied by the machine onto the specimen and where σ_b is the bending stress at the surface of the specimen.
According to the Weibull's theory, the failure probability in each subvolumedV is as follows, where <x> is the positive part of x:

$$P_F(dV) = 1 - e^{-\left(\frac{\langle\sigma_{xx}\rangle}{\sigma_o}\right)^m \frac{dV}{Vo}} \tag{2}$$

The failure probability $P_F(V)$of the specimen is calculated using the weakest link hypothesis. The volume V of the specimen is assumed to be partitioned in N subvolumesdVj. The specimen survives if each of its N subvolumesdVjalso survives. The survival probability $P_S(V)$ of the specimen can therefore be calculated as the product of the survival probability of each subvolume (Eq. 3).

$$P_F(V) = 1 - P_S(V) = 1 - \left(\prod_{j=1}^{N} P_S(dV_j)\right) = 1 - \prod_{j=1}^{N}\left(1 - P_F(dV_j)\right) \tag{3}$$

Because of the exponential form of the Weibull's law, we get:

$$P_F(V) = 1 - e^{\sum_{j=1}^{N} -\left(\frac{\langle\sigma_{xx}\rangle}{\sigma_o}\right)^m \frac{dV_j}{Vo}} = 1 - e^{\int_V -\left(\frac{\langle\sigma_{xx}\rangle}{\sigma_o}\right)^m \frac{dV}{Vo}} \tag{4}$$

The failure probability can finally be given as a function of the Weibull's stress :σ_W:

$$P_F(V) = 1 - e^{-\left(\frac{\sigma_W}{\sigma_o}\right)^m} \tag{5}$$

Where, the Weilbull's stress is calculated as follows :

$$\sigma_W = \left(\frac{\sigma_b}{\sigma_0}\right)\left(\frac{V_{eff}}{Vo}\right)^{1/m} \tag{6}$$

The effective volume of the specimen is defined as follows, using an integral over the volume V of the specimen:

$$V_{eff} = \int_V \left(\frac{\langle\sigma_{xx}\rangle}{\sigma_b}\right)^m dV \tag{7}$$

The value of *Vo* was set equal to 1mm^3. A fixed point iteration algorithm was used to determine the Weilbull's coefficients *m* and σ_o.

3.2 Results

In Figure3, the experimental data points are compared with the identified Weibull's law for this alumina. The Weibull coefficients were identified for Weibull's stresses σ_W ranging between 260 MPa and 450 MPa as follows:

- m=12,97
- σ_0=378MPa

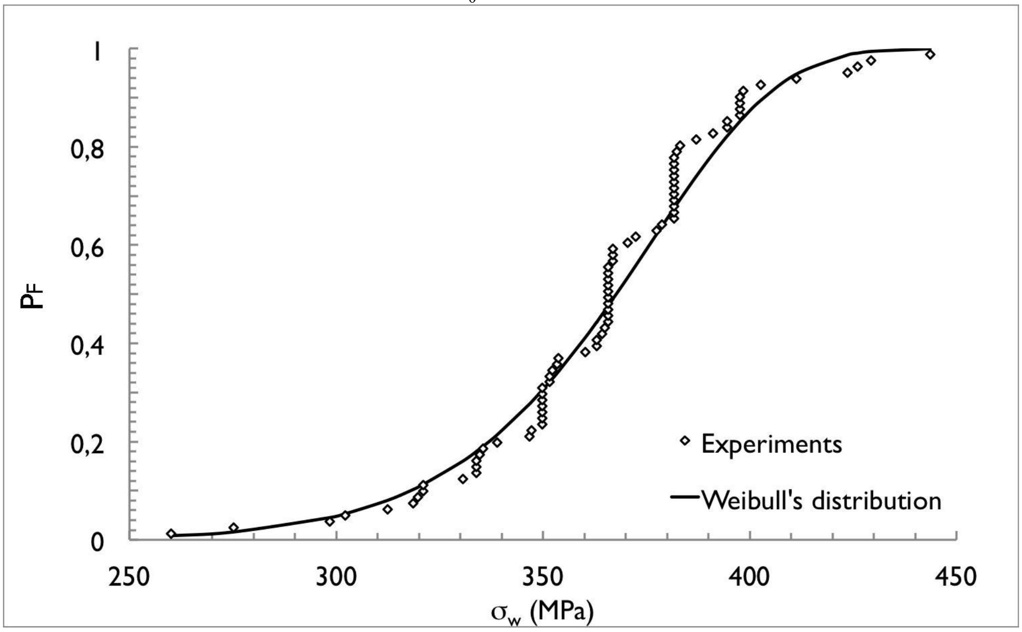


Figure 3. Identification of the Weibull's coefficient m and σ_0, P_F is the fracture probability and σ_W the Weibull's stress.

3.3 Four points bending tests

The pouring process of the alumina powder and solvents paste induces a preferred direction in the material. The pouring direction can possibly give orthotropic behaviour to the alumina foils. During the drying and the co-firing treatments the contraction of individual foils may be different along the two directions of the plane (the pouring direction and the transverse one). When stacking, the pouring directions of the foils are oriented at 90 ° from each other and the pileup is symmetric with respect to its mid plane. This type of pileupensures good dimensional accuracy and avoidsthe curvature of the substrate during the drying and co-firing treatments. However, it is believed that this pile up should be associated to the appearance of residual stresses inside the pileup.

Additional experiments were therefore conducted so as to determine these residual stresses. For this purpose, we assume that the principal residual stressesare uniform in each foil. We also assume that residual stresses are self equilibrated and that they can be linearly superimposed with applied stresses.

In order to identify these residual stresses, the following set of experiments was performed. We used a four points bending test in order to increase the effective volume of material tested and hence to reduce the width of the statistical distribution of the fracture load stemming directly from the probability of finding micro-defects in alumina per unit of volume (Figure 4)

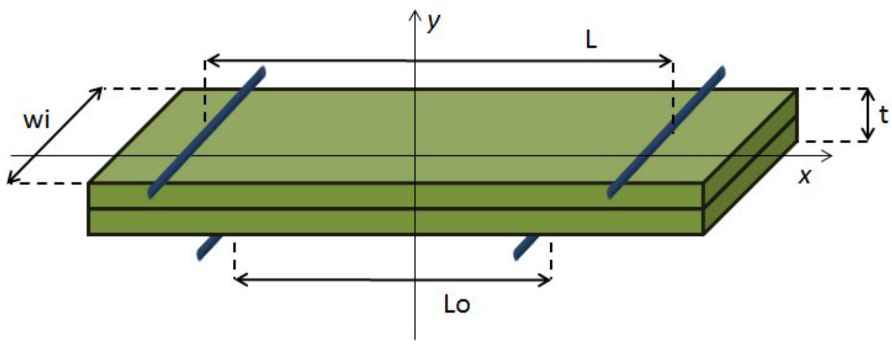
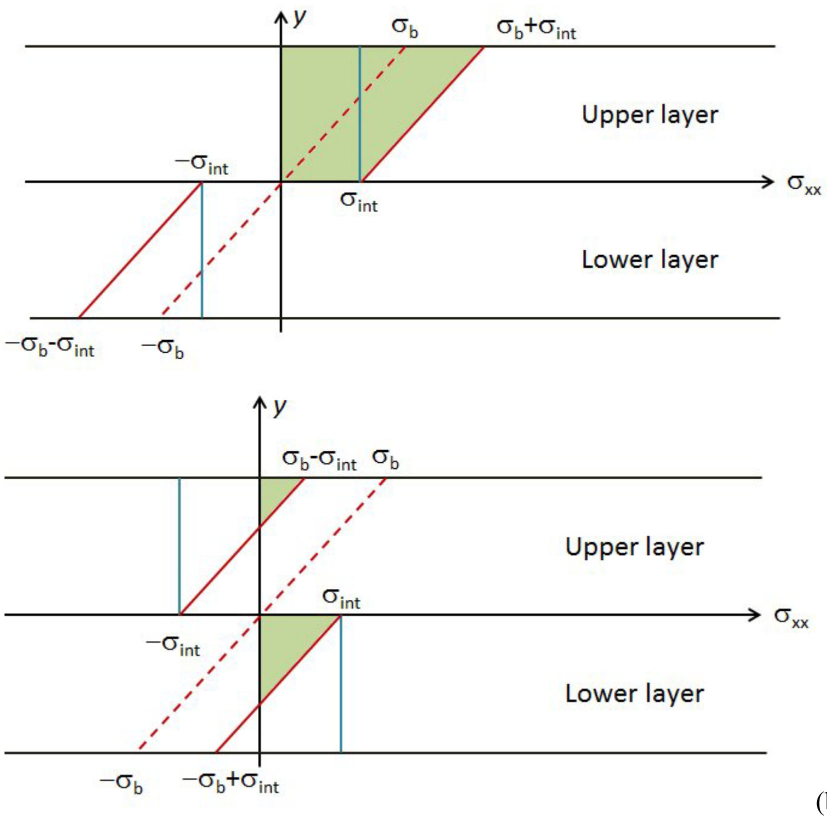


Figure 4. Four-bending tests conducted to determine residual stresses

In the experiments, the pouring direction of the upper foil may either be directed along the *y*-direction or at 90° from that direction within the plane of the foil. We had no way to know what is the pouring direction of the upper foil and hence that of the lower foil in the stacking. A part of the statistical distribution of the fracture load of the specimens during the four points bending tests should therefore be stemming from the random selection of the upper face orientation when the specimen is mounted onto the testing machine.

The tested specimen had a width w_l=5mm, a thickness t=200µm, the distance between the supports are L=24 mm and l_O=17 mm.

Between the two internal supports, the applied stress field is linearly varying through the specimen thickness. Two possible loading cases are encountered, according to the sign of the residual stress σ_{int} in each layer, as it is depicted in Fig. 5. Cracks initiates in subvolumes where the maximum principal stress is positive. In this new analysis, the internal stress modifies significantly the Weibull's stress because it modifies the stress distribution inside the specimen.



(a)

(b)

Figure 5. (a) the direction of the maximum principal residual stress is aligned with the x-direction within the upper layer, and at 90° from the x-direction within the lower layer. (b) the direction of the maximum principal residual stress is at 90° from the x-direction within the upper layer, and is aligned with the x-direction within the lower layer.

3.4 Results

In Fig. 6, the probability of failure is plotted versus the applied load at fracture. The experimental data obtained during these experiments were compared with the predictions made using the Weibull's law identified using the three points bending tests and applied to this four points bending problem without considering residual stresses. It is quite obvious in this graph that there is a significant discrepancy between the experiments and the predictions.

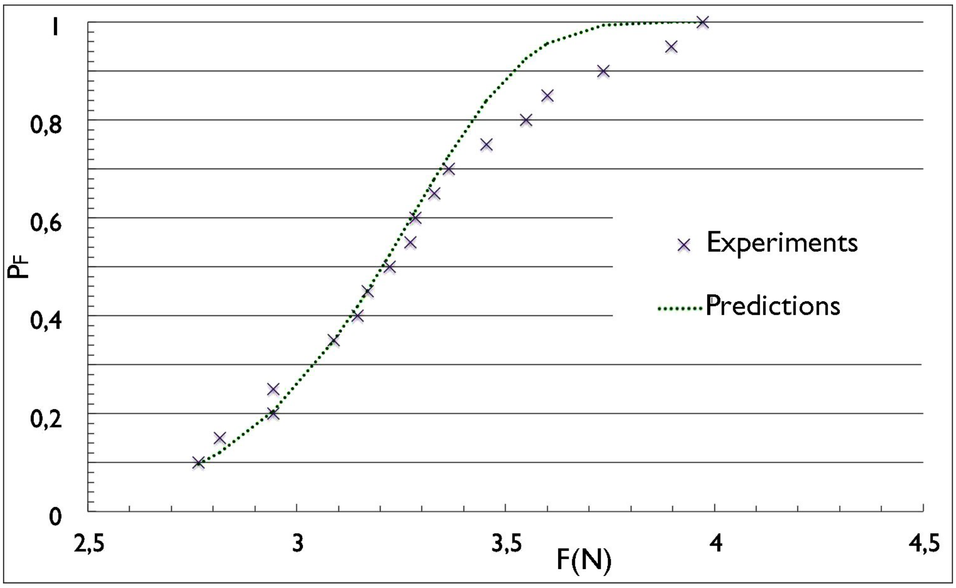


Figure 6.Comparaison between the prediction of the Weibull's law identified using three points bending tests(solid line) and experimental data (crosses)

4 RESIDUAL STRESSES DETERMINATION AND DISCUSSION

The stress field inside the specimen is now as follows between the two supports :

$$\sigma_{xx}(case\ 1) = \sigma_b \frac{2y}{w_i} + \sigma_{int} \times sign(y) \qquad \text{or} \qquad \sigma_{xx}(case\ 2) = \sigma_b \frac{2y}{w_i} - \sigma_{int} \times sign(y) \quad (8)$$

The effective volume was calculated for each case as a function of the residual stress level for each case as explained in Eqs. (2) to (8). Then, the failure probability for each case was determined using the Weibull's coefficients determined in three points bending tests for each case. To visualize the effect of internal stresses, the predicted failure probability functions were plotted for both cases in Fig. 7 considering a residual stress equal to $\sigma_{int} = 23\ MPa$.
The failure probability of our specimens is now calculated as follows, considering that the two cases do have the same probability :

$$P_F(case\ 1\ or\ case\ 2) = \frac{1}{2}\left(P_F(case\ 1) + P_F(case\ 2)\right) \quad (9)$$

In Fig. 7, the experimental results are also compared with the predictions using Eq. 9. The value of the internal stress was adjusted at $\sigma_{int} = 23\ MPa$ so as to get the best fit between the predictions and the experimental results.

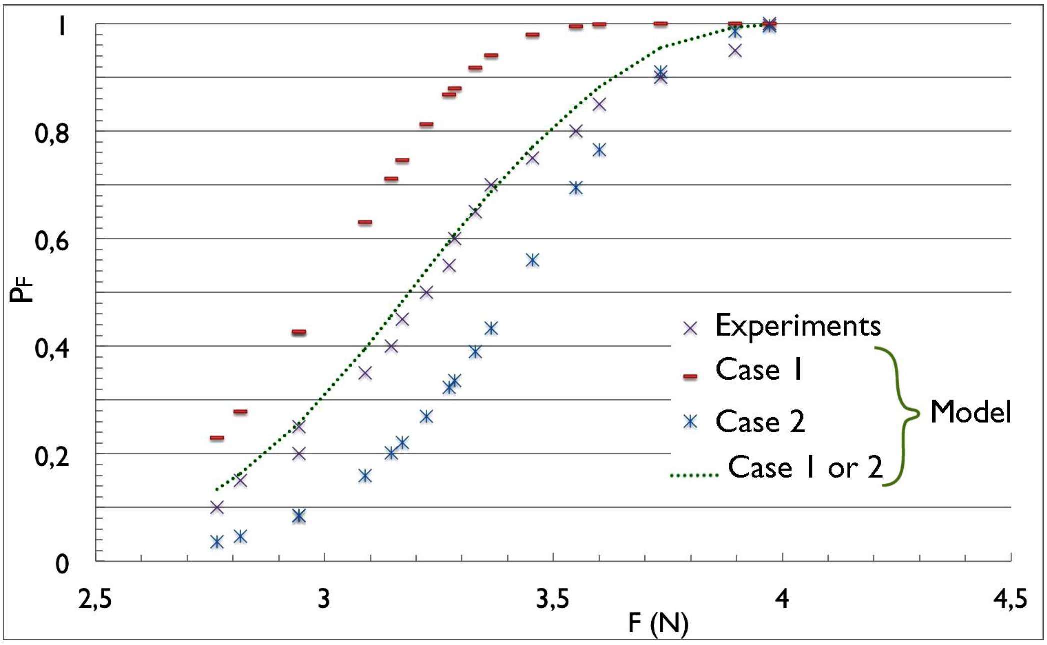


Figure 7. Simulation taking into account internal stress

The value of the internal stress $\sigma_{int} = 23\ MPa$ that was identified is quite moderate, but it applies to a large volume of material and can have therefore a significant effect on the fracture load of the pileup.

In the substrate, the sign of this internal stress changes abruptly at the interface between one layer and its neighbour. Ten microns thick tungsten circuit lines are printed on this interface. The value of the internal stress is believed to be significant to predict the cyclic delamination of the circuit lines at the tungsten-alumina interface during thermal cycling. To analyse this problem, the measured internal stresses will be added to the finite element model of the 3D HTCC substrate using a fictitious temperature variation and a non-isotropic thermal expansion for each layer.

The Weibull's law identified for the alumina can also be used to determine the failure probability of the substrate during thermal fatigue cycling. However, it is important to underline that below a Weibull's stress of 260 MPa, we only know an upper bound for the failure probability (Fig. 3). The same remark is also true for the other side of the curve, for which we only have a lower bound of the failure probability.

In order to reduce the uncertainty on both sides of the curve (Fig. 3), special specimen were prepared to be tested in four points bending conditions. A small hole was pierced (with a diameter of 50 microns) to create a stress concentration and reduce the effective volume and hence the Weibull's stress for the same loading conditions. These samples will also be used to determine the fracture thoughness of the alumina.
Experiments are also performed to determine the thermal expansion and the thermal conductivity of an individual ceramic foil along the pouring and the transverse direction and that of a pileup of two ceramic layers.

5 CONCLUSION

This study was devoted to the analyses of damage mechanisms of tungsten-alumina co-fired 3D subtrates.

The main problem encountered stems from the heterogeneity of the structure. As a matter of fact, alumina is a poor thermal conductor and has a low expansion coefficient, while tungsten lines have higher expansion coefficient and capability of thermal conduction. Since both materials are co-fired to form the 3D structure, thermal internal stresses arise because of ambient temperature variations and thermal dissipation in operating conditions due to the Joule effect.

In addition, the complexity of the geometry is at the origin of stress and strain singularities, in particular at the interfaces between the ceramic layers or around holes created for various purposes that act as stress concentrators.

Residual stresses stemming from the material orientation induced in alumina foils by the pouring process were determined using fracture experiments. These residual stresses change abruptly within the substrate at the interface between two layers of ceramics and hence may contribute to the fatigue damage of the substrate.

The fracture of the alumina is modelled by a Weibull law, which has the advantage of accounting for gradient and scale effects. The Weibull's coefficients were determined for the studied material.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] S. Pietranico, Analyse de matériaux pour la modélisation des mécanismes de défaillance dans les modules électroniques de puissance, PhDthesis, ENS Cachan, 2010
[2] S. Pietranico, S. Pommier, S. Lefebvre, Z. Khatir and S. Bontemps, *Microelectronics Reliability*, 49, 2009, 1260-1266.
[3] S. Pietranico, S. Pommier, S. Lefebvre and S. Pattofatto, *International Journal of Fatigue*, 31, 2009, 1911-1920.
[4] L. Dupont, Contribution à l'étude de la durée de vie des assemblages de puissance, PhDthesis, ENS Cachan, 2006.
[5] A. Houssam, et al. „*Journal of the European Ceramics Society*, Vol. 15, I. 5, 1995, pp 425-434.
[6] Y. Nagatomo and T. Nagase (2000), The Study of the Power Modules with High Reliability forEV Use, 17th EVS conf., Montreal, October 2000.
[7] J. Lemaitre and J.-L. Chaboche, Mécaniquedes matériaux solides, 2nd éd. Paris Dunod, 2004.
[8] W. Weibull, *IngeniörsvetenskapsakademiensHandlingar*, volume A (151), 1939.