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Thermo-Mechanical Behavior of Power Electronic Packaging Assemblies: from Characterization to Predictive Simulation of Lifetimes

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Abstract. This article deals with thermo-mechanical behavior of power electronic modules used in several transportation applications as railway, aeronautic or automotive systems. Due to a multi-layered structures, involving different materials with a large variation of coefficient of thermal expansion, temperature variations originated from active or passive cycling (respectively from die dissipation or environmental constraint) induces strain and stresses field variations, giving fatigue phenomenon of the system. The analysis of the behavior of these systems and their dimensioning require the implementation of complex modeling strategies by both the multi-physical and the multi-scale character of the power modules. In this paper we present some solutions for studying the thermomechanical behavior of brazed assemblies as well as taking into account the interfaces represented by the numerous metallizations involved in the process assembly.

INTRODUCTION

Since several years, the constant evolution of power electronics has resulted in the increasing requirement in integration of a large amount of devices. For example, in the railway industry, one of the most important innovations is probably the introduction of three-dimensional semiconductors (IGBT chips) in power converters resulting in increased power switched and a high profit in volume and mass with respect to the planar components (thyristor or GTO transistor). This evolution has also led to a shift from press-pack technology to solder joint.

From the integration of the components results an assembly composed of parts with a large difference of scales. While the current dimensions of a module are of about ten centimeters, the surface area of the chip is of the order of the centimeter square for a silicon IGBT and a few millimeter square for a silicon carbide chip. In the thickness, the characteristic dimensions of the assemblies vary from a few millimeters (3 mm for an AlSiC composite base plate, 0.6 mm for the dielectric ceramic substrate, 0.2 mm for the metallizations and 0.1 mm for the chips), a few microns for finishing metallizations.

Technological advances in the context of power integration result in the confinement of the zones of interest (connection zones between the different parts), changes in scale and rapprochement of the different physical problems inevitably induces couplings between each other.

The interest of the simulation for these systems is to give access to many quantities (stress, strain, temperature, strain energy, etc.) which are not accessible to the experimental measure, due to the confinement of the system, small scales involved and the electric environment (high voltages, currents, electric fields). The elaborated models make it possible to study the behavior of the power electronics modules with respect to various stress conditions, but also to dimension and optimize them through the implementation of conventional or reliable procedures. In this paper we present some thermomechanical methods used to optimize power electronic modules in relation to specific damage phenomenon which occurs in the solder joints and near the die environment.

POWER ELECTRONIC MODULES

Definition and structure of a module

The power electronics modules are assemblies that enable delivering convenient electrical power to an actuator. Whatever the field of application, railway, aeronautic or automotive, these devices are increasingly used, whether for the purpose of delivering more power for an ever smaller volume, or because they are integrated into other systems. As an example, the converter module for the Airbus A380 thrust reverser system (ETRAS) is located near the jet engine in a non-pressurized environment and is therefore highly stressed in terms of pressure, temperature, relative humidity, vibration, etc.

Typically, the modules are constituted of a polymer protection case (polymer packaging) with no external connections (Figure 1, a and b). Inside this packaging there are one or more assemblies which are generally built around an insulating substrate comprising a ceramic plate (alumina, aluminum nitride, etc.), bonded between two metallizations, usually copper or aluminum. Depending on the production process, the term DBC (direct bonded copper) or AMB (active metal brazing) substrate is used. The components (diodes, IGBT and others) are brazed to one side of the substrate, while the other side is brazed to the base plate (copper, Al-SiC, etc.). The base plate has a thermal function for the diffusion of the heat flux to the cooling system, and a mechanical role for the attachment of the module. The electronic components are generally connected together by thermo-welded wires bonding.

The shown previous module is planar type and has the disadvantage to be cooled by only one single face. In order to increase the cooling capacity of the modules, several technical solutions have been developed to allow extraction of the thermal flux simultaneously by the upper and lower surfaces of the modules [1-3]. The Power Electronic Research Laboratory (PEARL) has proposed to develop a new 3D structure, for which the connections between the components are obtained by small cylinders or balls of copper, here named bumps, connected by brazing to a second upper metallized substrate (Figure 1, c).

Here we provide some basic advice for formatting your mathematics, but we do not attempt to define detailed styles or specifications for mathematical typesetting. You should use the standard styles, symbols, and conventions for the field/discipline you are writing about.

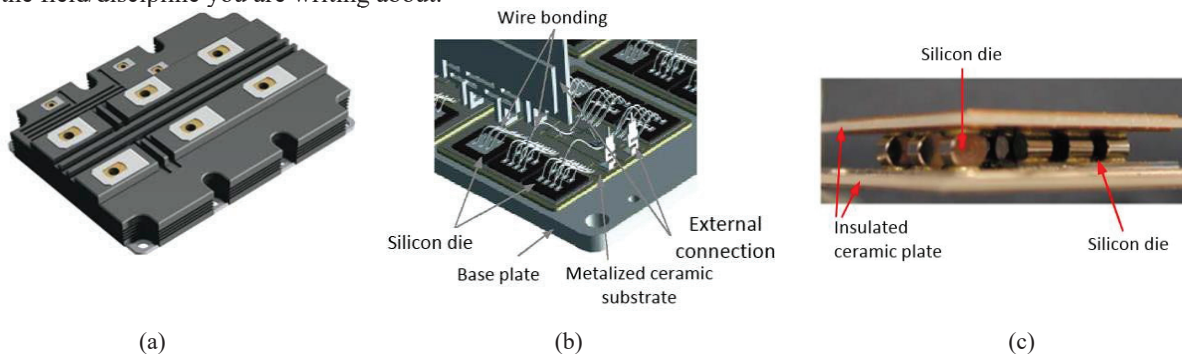


FIGURE 1. Power electronic module, global and internal view of a planar type ((a) and (b) respectively), (c) internal view of a double side assembly using bump connections

A module thus presents as a millefeuille composed of layers of different materials bounded to one another. When the temperature of the assembly evolves, the various coefficients of expansion induce a "bimetal" effect (bending of the structure), which generates strain and stresses in the assembly. Thermal loading is due to the thermal dissipation of silicon chip (active cycling), and/or is fixed by the environment (passive thermal cycling). The resulting temperature of the module come from the maximum temperatures allowed by the chip. This temperature is generally 125°C for silicon chips, but can rise to 250°C for silicon carbide components or even 300°C considered for a diamond die. During functioning, the modules could be subject to various fault modes that can be classified according to the zone concerned. A non-exhaustive failure modes could be listed in each zone:

- Chips (burn out, latch-up, fracture, etc.) [4],
- Wire bonds (lift off, fracture, corrosion, etc.) [4, 5],
- Solder joints (thermomechanical fatigue, micro-structure changes, electro-migration, etc.) [6-9],

- Polymeric packaging (wearing out, partial discharges damages, etc.) [10, 11],
- Ceramic substrates (brittle fractures, partial discharge damages, etc...) [11, 12]

Solder joint reliability

Under wide temperature swing amplitudes, the solders degradations represent one of the most critical failure modes of power modules, as observed experimentally, shown in several publications [12] and illustrated on Figure 2. They are due to the cyclic stresses generated in the assemblies by the combination of coefficient of thermal expansion mismatch of the soldered parts, and the cyclic variations of the temperature [3, 9, 12]. Then, they are subjected over the module lifetime to thermomechanical fatigue, and their failures directly affect the module electrical function by causing chips excessive heat (burn-out) or by simply interrupting the electrical paths.

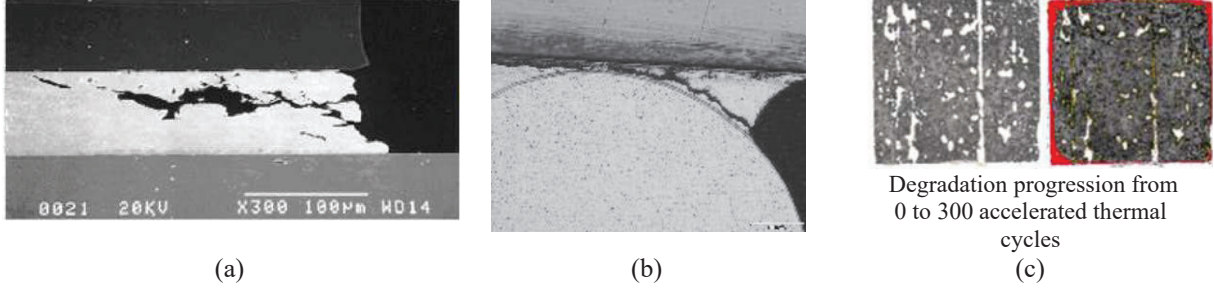


FIGURE 2. Thermomechanical damage after power and thermal cycling in, (a) die solder joint, (b) power bump solder joint, (c) die solder joint [41]

Thermomechanical life time calculation

The classical way for the thermomechanical modeling of fatigue failure consists in representing the number of stress cycles leading to the failure N_f , as a function of physical quantities characteristic of each cycle (X), namely: $N_f = f(X)$. The variable X is a quantity (stress, strain, energy), measured or calculated. In the particular case of solder joints, many approaches can be used. They are based on strain, strain energies or damage evaluation [7, 13, 14, 15]. The most commonly used models are based on strain (total strain [6], creep strain [16]), or on energy (total strain energy dissipated per cycle [17], plastic strain energy [18], inelastic strain energy [15]).

Heinrich's model is interesting because of its relative simplicity of implementation and its precision [19]. It takes into account the energy dissipated by instantaneous plastic strain and also viscoplasticity. The average number of cycles before initiation of a crack (\bar{N}_f) is then expressed by the relation:

$$N_f = K_1 (\Delta W_{ave}^{in})^{K_2} \quad (1)$$

where, K_1 are material dependent parameters and ΔW_{ave}^{in} the inelastic strain density energy. This value is calculated from the finite element model of the connection, making the weighted average of elements to be considered. The relationship is as follows:

$$\Delta W_{ave}^{in} = \frac{\sum \Delta W_e^{in} V_e}{\sum V_e} \quad (2)$$

where, ΔW_e^{in} is the dissipated strain energy density by the e^{th} element and V_e is the associated volume. This damage metric makes it possible to reduce mesh dependency and geometric singularities effects.

The previous model gives a lifetime before a crack appear. To foresee the complete rupture of the analyzed structure, it is mandatory to model the crack propagation up to its critical size. Darveaux proposes such a formulation [14], associating the initiation model with a model of propagation of the crack as a function of the inelastic strain energy density (eq 2).

$$\begin{cases} N_0 = K_1 (\Delta W_{ave}^{in})^{K_2} \\ \frac{da}{dN} = K_3 (\Delta W_{ave}^{in})^{K_4} \end{cases} \quad (3)$$

where, a is the crack length and N the number of cycles to failure. K_i are four material dependent parameters which must be identified. The identification of the fatigue laws parameters is done from a finite element updating method which is described in [20]. The tests are typically accelerated test, with a simplified design. Indeed, designed tests must allow, on the one hand, to preserve the similarity of the failure mechanisms to be studied, and on the other hand, a model giving reasonable calculation times with respect to the iterative process involved.

DIFFERENT MODELING STRATEGIES AND RESULTS

To model power electronic modules, one approach consists in using semi-analytical models that take into account the physical behavior of different parts of the system (thermal behavior, mechanical stiffness, electrical resistance, etc). These models are implemented on multi-physical platforms such as Matlab-Simulink©. The main disadvantage of this modular approach is the lack of analytical models to translate the actual behavior of the various physics. From the mechanical and thermomechanical point of view, the use of numerical models generally formulated using the finite element method is the almost unanimous rule. They integrate the necessary physics (thermal, mechanical, electrical with the possible couplings), and the real geometry of the problem.

When one wishes to build a complete model of a module, one important problem concerns the computing time which can become unacceptable due to various factors. First there is the approximation of the geometric domain and the number of elements required in the small-dimensional areas. Then, the characteristic time constants of the different physics considered are varied (of the order of millisecond for the chip to several tens of seconds for the module). Finally, there is the multi-physical, non-linear and coupled aspect of the problem.

One solution consists in limiting the size of the models by the legitimate use of structural elements (plates, shells, springs, thermal resistance, etc.), and the implementation of the technique of structural zoom (or sub-modeling, [21]). For a complete assembly, it is indeed possible to model the baseplate, the substrates, the chips and the solders by means of mechanical and/or thermal shell elements and to replace the bumps by 3D springs elements, possibly nonlinear. We obtain then a first global model, 3D shell, of the structure (Figure 3a, b). A solid 3D model of the area of interest is then developed. It may be a part of the assembly or a single connection (bump for example, Figure 3c). The boundary conditions of this model will be based on the results taken from the global model. Thanks to its small size, the detail model can be correctly refined, without requiring too large calculation resources.

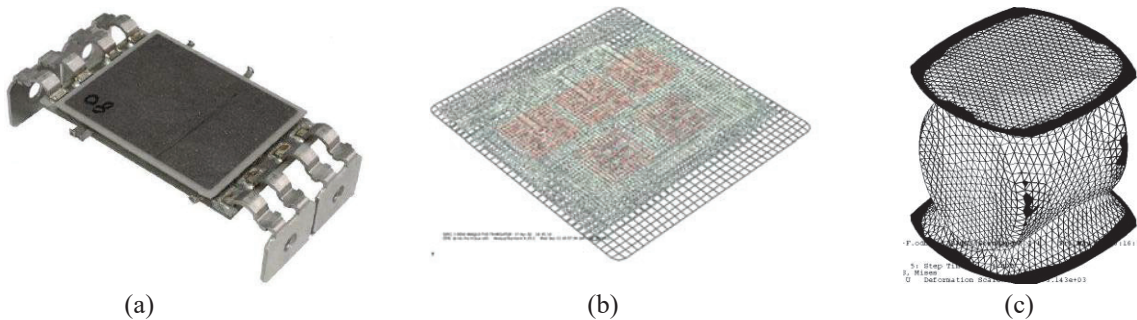


FIGURE 3. (a) Example of a switch modeling, (b) global structural model, (c) 3D solid model of a bump junction

This technique was used to calculate a switch developed at the PEARL laboratory (Figure 3a). A switch is a part of a module composed of two chips and two diodes, connected to two ceramic metallized substrates through several bumps connections. The thermomechanical simulation is of the uncoupled type, corresponding to the fact that thermal and mechanical problems are not simultaneously solved. In our example, we have a global 3D thermal shell model (with thermal resistances instead of connections), and a global 3D shell mechanical model (with 3D spring instead of connections). The sequence of the various calculations is carried out according to the block diagram (Figure 4). A thermal transfer analysis is first performed on the 3D shell model and the temperature solution is introduced into the global mechanical model. When the thermal and mechanical solutions have been evaluated using this model, they then become the boundary conditions for the solid 3D solving of the bump connection. The advantage of this approach is

to make possible to evaluate several configurations of bumps (variation of the geometry of the inserts: balls, horizontal or vertical cylinders) by replacing only the values of the thermal resistances and mechanical equivalents in 3D shell models and evolving the mesh in solid 3D mechanical computation of bumps.

This method is of course interesting to reduce the computational time but presents some disadvantages. Indeed, even executing all the calculations on a single software, it is generally necessary to control the procedure with external scripts to automate it. Programs are also need to allow, for example, to extract results from of the global model into boundary conditions for the local model. Finally, for this strategy the mechanical calculation of the global model, the used constitutive behavior law is generally at best elastoplastic. Only the solid 3D detail model, integrates the elasto-viscoplastic model for solder joints. If one wishes to take account of the nonlinear behavior induced by the connections, it will be necessary to add a computational loop allowing to update the characteristics of the global model.

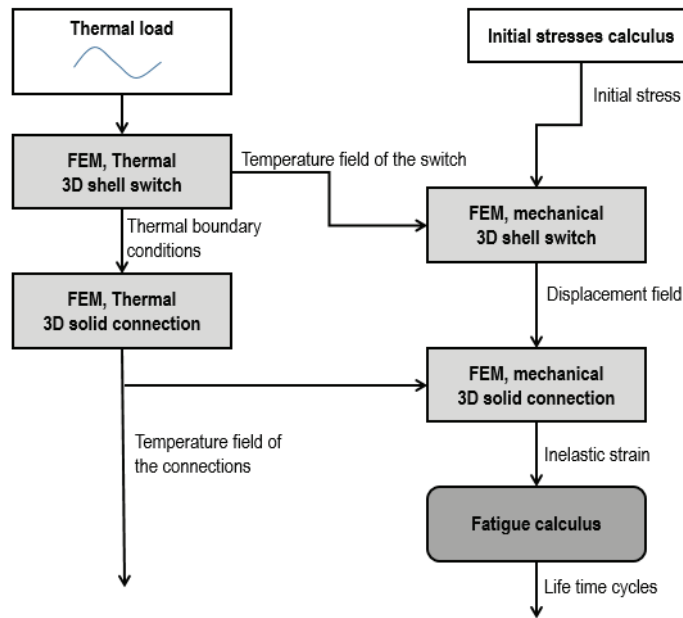


FIGURE 4. Diagram of the calculation steps of an uncoupled thermal and mechanical model using the submodeling technique

An alternative to previous technique is to use a complete 3D model of the module or switch. Even though computing times can be important the set-up of these models is more intuitive and is fairly easily guided by software tools. As an example, two types of structures of a same module have been studied using 3D finite element modeling. These models allowed the implementation of analyzes based on numerical experiments and reliability calculations.

The two structures are shown in Figure 5. These modules have the special feature of allowing double-sided cooling thanks to the upper and lower base plate. The components are silicon IGBT chips and SiC diodes. The brazing is of PbSnAg type for soldering backside of the chips and SnAg for all the other connections. The behavior of the solder joints are of the viscoplastic type, modeled by the Anand constitutive law [22, 23].

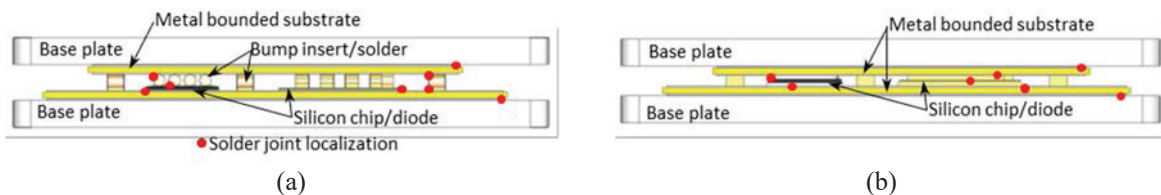


FIGURE 5. Sectional view of the internal structure of the two modules (a) with bump connections, (b) with direct solder assembly

For the numerical study, the structures was designed such that two planes of symmetry can be considered in order to limit the size of the models. The dimensions of the assemblies are 50 mm × 50 mm × 3 mm (base plate) and the smallest 0.1 mm (thickness of the solder chip and base plate). The mesh is made from linear and quadratic bricks and

tetrahedra. The interfaces between the layers are assumed to be perfect. The convergence study was carried out on the strain energy density calculation at different points of the solder joints. The required element size for a good accuracy is 0.2 mm. The thermomechanical simulations are carried out in uncoupled mode for passive cycling (temperature variation between -55°C and $+125^{\circ}\text{C}$), and fully coupled mode for active cycling (250 W dissipated in the chip and forced convection coefficient equal to $8000 \text{ W}/(\text{m}^2\text{K})$ for the cooled faces).

Figure 6 allows to compare the resulting temperature profiles in the assemblies for the case of active cycling. For the two proposed structures, the distribution of the thermal flow through each of the upper and lower faces of the modules was evaluated. In the case of direct connection solder, a good thermal equilibrium is observed with a flux ratio of 47% to the upper surface and 53% to the lower surface. On the other hand, in the case of solder bump assembly, the proportions are 26% against 74%. A good flow balance leads to a better distribution of thermal and thermo-mechanical stresses in the assemblies, and in particular in the chips. The maximum operating temperatures for structures with direct solder connections are 17.3°C lower than those obtained with inserts brazed connections. Compared to a structure of the same composition/function, but connected with wires bonding, the gain on the maximum operating temperature is 37°C . To evaluate the stresses in assembly, a first step is need to simulate the manufacturing process. This step is at the origin of initial stresses in the module. Following this first step, the load profile (active or passive cycling) is simulated. Figure 7 shows the inelastic strain energy density fields in the most stressed areas: connection solders in bump solution (Figure 7a) and grid solder in direct solder case (Figure 7b).

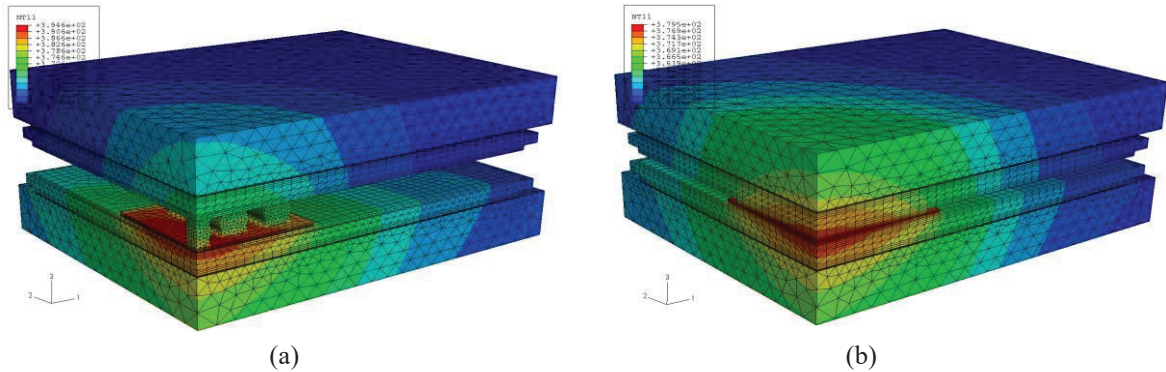


FIGURE 6. Thermal field (K) in the assemblies: (a) with bump connections, (b) direct solder assembly

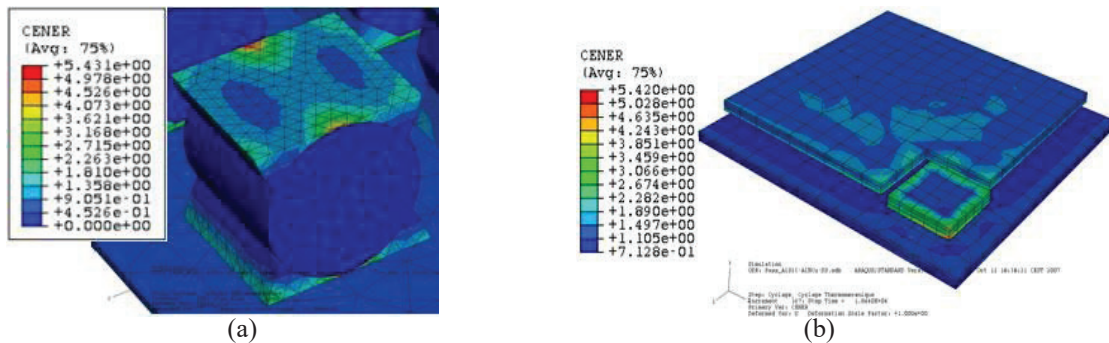


FIGURE 7. Inelastic strain energy density distribution in connections (mJ/mm^3): (a) with bump connections, (b) direct solder assembly

To evaluate the fatigue life time of the modules, the analysis of the evolution of the hysteresis loops (stress/strain diagrams) during cycling must be done. It shows a cyclic stabilization of the energies involved, illustrated in Figure 8 (a) and (b), respectively for bump or direct solder connection assembly.

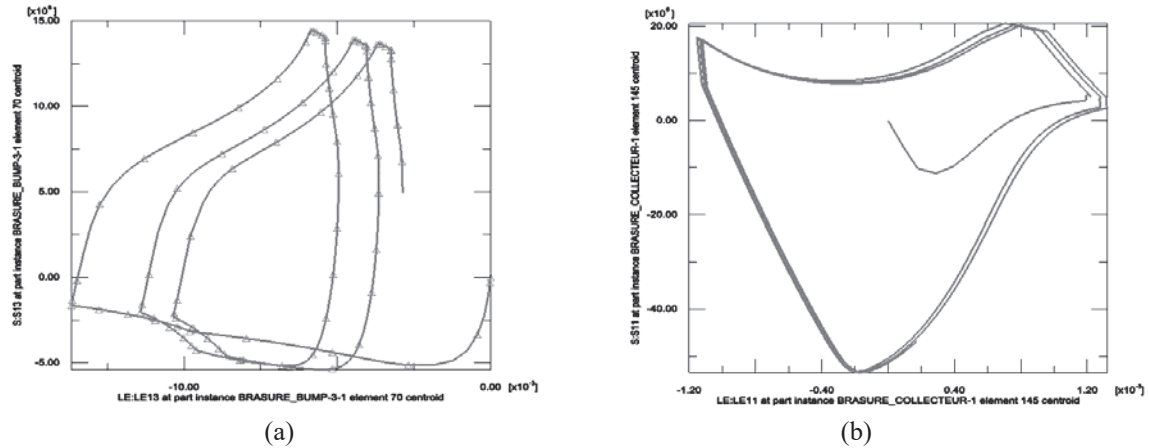


FIGURE 8. Stabilization of stress / strain cycles in solder joints: (a) bump connections, (b) direct solder connection

CONCLUSIONS

The modelling of the failure of power electronics modules under thermomechanical loading is of prime interest in the design and optimization of these systems. Several difficulties have to be solved to obtain satisfactory results in time compatible with the cycle development of the modules. The methodology requires precise investigations as a preliminary study in order to identify the failure modes of the modules and then to model them precisely. For modelling, in addition to the multi-physical and multi-scale aspects, taking into account materials non-linearity through the viscoplastic behaviour of brazing is a difficult point. Finite element models are based on the modules data, such as the geometry of the various assembled parts, the materials used with their thermomechanical behaviour laws and their thermomechanical fatigue laws, loading (thermal losses in components), mechanical and thermal boundary conditions, etc. Fatigue laws are identified from experimental results (passive or active accelerated cycling).

In this paper, we have presented two possible ways of modelling modules. The uncoupled modelling of physics and scales may in some cases yield satisfactory results but becomes very complex to set up if we wish to enrich the model. Full solid 3D models, although a high computing time, provide fairly simple access to results of interest for these studies. Some results have been presented, allowing the comparison of two different structures of power electronic modules.

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