Modelling behaviour of large area solder joints

Proving long-term mechanical stability and reliability

The creep behaviour of solder is incorporated into the bending analysis. Modelling has been kept simple, but the computational assessment of creep in a solder layer compares well with experimental results.

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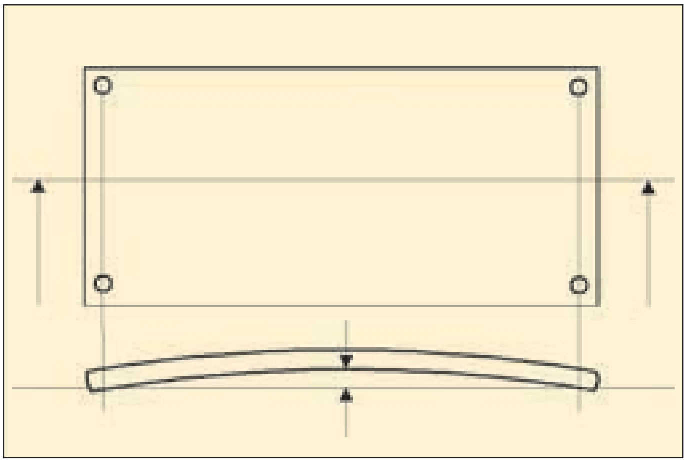

Figure 1: *Relative bending of the baseplate of the module after soldering, schematically*

Packages of power modules are designed to show a slightly convex shape of the baseplate in order to achieve a reasonable thermal contact between the module and the heat sink when the power module is mounted. During manufacturing, soldering of materials with differences in thermal expansion coefficients will lead to bending of the "bi-material" composite, e.g. the silicon chip to substrate (usually DCB = direct copper bond Al_2O_3 or AlN) or the DCB-substrate to baseplate joint (Cu or MMC = metal matrix composite). Especially the large area solder joint between DCB-substrate and Cu baseplate is known to induce a certain curvature into the baseplate immediately after cooling down from soldering. The curvature will relax to a certain extent during module finishing, storage, shipping, and use which makes the prediction of the shape of the baseplate difficult. The present paper proposes a model to assess the creep behaviour of such large area solder joints in order to predict the state of bending after soldering and the amount of relaxation of bending with time.

The slightly convex shape of the module's mounting plane is achieved by an initial deformation of the Cu base-plate (3 to 5 mm Cu typically) to a certain radius of curvature. During manufacturing of the module, the DCB-substrates (with soldered terminals, Si-dice, and the Al-wires bonded) will be soldered to the baseplate which is typically done in a vacuum soldering furnace to achieve a low void content in the large area solder joint. After cooling down from the melting temperature of the solder, the thermal contraction of the Cu baseplate will bend the multi-layer composite due to its large CTE (coefficient of thermal expansion) compared to the DCB-substrate and due to its high stiffness. Therefore, the initial convex shape will be flattened or even deformed to a concave curvature leading to gaps when mounting such a module to a heat sink. The state of deformation is schematically shown in *figure 1*.

It is well known that the curvature introduced by cooling from the solidification temperature of the solder alloy will relax to some extent with time, because the bending moment to deform the DCB and the baseplate elastically is carried by a soft solder joint. Up to three temperature excursions to approximately 150°C/8 h (curing of adhesive, soft and hard encapsulation) are part of the manufacturing steps. Since solder alloys creep even at room temperature with a small load applied, the relaxation of the curvature can be observed for days or weeks. An example of experimental work is shown in *figure 2*, depicting the relaxation of the baseplates' shape during module manufacturing and storage.

Analytical equations are known to calculate elastic bending of layered composites. An extensive experimental and finite-element-modelling study (FEM) of the stress state in soldered composites (Si chip on substrate) has been published, but without addressing the time dependent creep behaviour of the solder materials. Obviously, creep of the solder layer strongly affects lifetime during passive temperature cycling, because fatigue cracks will start to grow at the periphery of the DCB, the site with maximum shear strain.

Incorporating the creep behaviour of solder materials into the bending analysis of layered composites is the thematic. Modelling approaches have been kept simple, but it will be shown that even with strong idealisations the computational assessment of creep in a solder layer compares well with experimental results.

Displacements have been measured according to *figure 1* (positive displacement = convex shape). The graph (*figure 2*) shows a summary of some measurements which have been made during module manufacturing and time thereafter. The convex shape of the baseplate before soldering turns to be concave after soldering. The curvature remained slightly concave up to approximately 500 h after manufacturing (*figure 2*). Since the baseplate and the DCB are deformed elastically due to CTE differences, a driving force towards the previous curvature exists. Creep of the solder layer relaxes the internal stresses in the “bi-metallic” composite

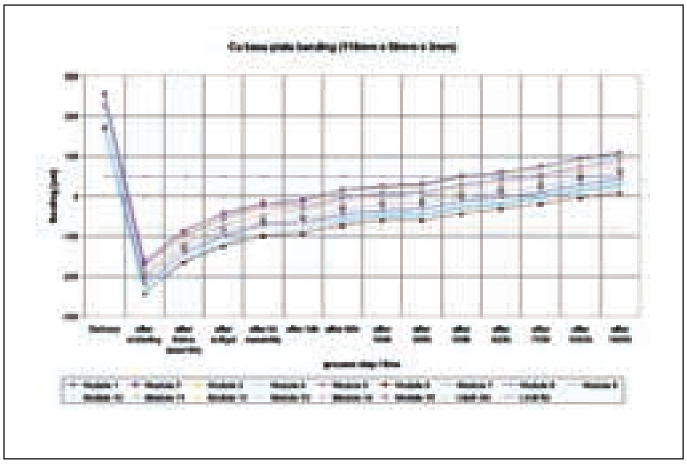

Figure 2: *Measurement of the baseplate curvature during module manufacturing (soldering and 3 temperature excursions of approximately 130°C/1 h) and thereafter. “Bending” is defined as the height of the baseplate’s midpoint compared to the supports at the short edges of the module.*

(here Cu and DCB) for a long period (*figure 2*).

The model proposed here is mainly based on well known analytical equations describing the creep behaviour of materials, particularly, the soft solder used for the attachment of the DCB to the baseplate. Therefore, some simplifications of the geometry must be made to assess the state of stress and strain in the solder layer between DCB and baseplate. The latter two are idealised by materials with a mean CTE and Young’s modulus comprising a bi-metallic composite. The bending moment acting on top and bottom layer (DCB and baseplate, respectively) is carried by the solder layer which is mainly stressed by in-plane shear forces. It can be shown that tensile (or compressive) stresses are negligible compared to the shear stresses; therefore, the shear stress τ is half of the von Mises stress σ. The force which is necessary to deform the top and bottom layer can be calculated from linear elastic theory of bending multi-layered composites (Timoshenko’s analysis).

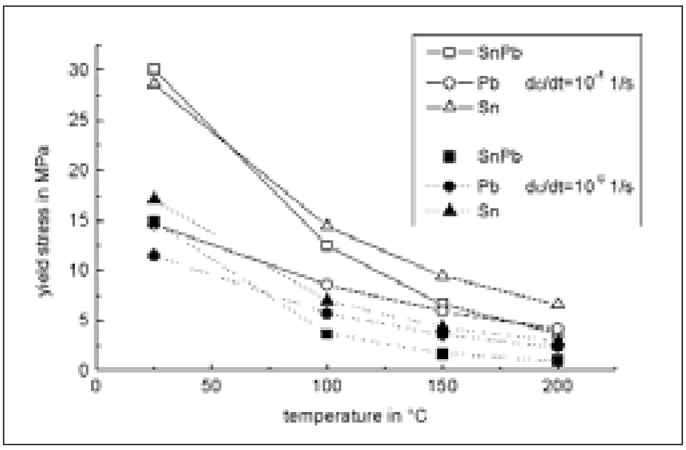

Figure 3: *Yield stress with an applied strain rate at a given temperature, constitutive relation for SnPb eutectic, Pb, and Sn. Creep data taken from Winter, Wallach; Soldering & Surface Mount Techn. 26 (1997) 61-64.*

This force must be equal to the mean shear stress in the solder layer multiplied by the area of the solder joint. The shear stress at the temperature given will enable the solder layer to creep with a certain velocity into the direction which allows the bending forces to relax. Additionally, the bending-theory calculation gives the relaxed geometry at any temperature which defines the maximum amount of displacement (or shear strain) in the solder layer. The creep behaviour of a material, i.e. the steady state strain rate being a function of stress and temperature, is, for instance, described by following type of constitutive relation:

$$\dot{\varepsilon} = A1 \cdot \sinh(A2 \cdot \sigma)^n \cdot \exp\left(\frac{-Q}{RT}\right)$$

A1, A2, n and Q (activation energy) are material parameters and R is the universal gas constant. T is the absolute temperature and s the von Mises stress. Parameters of solder alloys to use such constitutive creep laws are partly known. Typical data are given in *table 1* and the following diagram (*figure 3*) shows some results.

The maximum local strain rate $\dot{\varepsilon}$ (or the shear strain rate $\dot{\gamma}$) in the solder layer of a composite caused by temperature changes can be assessed for the fully relaxed state (i.e. without bending) with the distance from the centre of the layer composite l_D, the solder gap thickness h, the difference between the coefficients of thermal expansion Δα of the joined layers, and the heating or cooling rate $\dot{T}$.

$$\dot{\varepsilon} = \frac{\dot{\gamma}}{2} = \frac{l_D \cdot \Delta\alpha \cdot \dot{T}}{2 \cdot h}$$

This maximum strain rate will of course not be reached because the shear stress arising in the solder layer will lower the rate of deformation which results in a bending moment acting on the composite. Shear stress and strain rate in the solder layer are for simplicity replaced by their mean values. The mean shear stress and the lateral size of the DCB are related to the force to produce a certain curvature of the composite. Utilising the mean value of the actual shear stress in the solder layer which is linearly related with curvature, the strain rate at the given temperature is calculated. Now, a numerical procedure is employed to add some hundred creep deformation increments (i.e. time steps) while the bending moment is stepwise decreased because each shear increment relaxes the curvature. Thus, the behaviour of the composite (DCB and baseplate) can be calculated with temperature and time.

An example of a calculation of several temperature swings during module manufacturing and the time of storage is given in *figure 4*. Comparison is done with the experimental data of *figure 2*. The geometry here can be described by following data: Two DCB substrates of 48 mm in length (0.3 mm Cu, 0.38 mm Al_2O_3, 0.3 mm Cu) were soldered with near-eutectic SnPb40Ag1 alloy (approximately 0.2 mm solder gap) to a Cu base-plate of 3 mm thickness. The creep rate is governed by the length of the DCB, whereas "bending" has been determined along the entire module, i.e. with both DCBs contributing to the total displacement. For convenience, only the displacement difference between the actual shape and the initial one is shown; any offset due to initial bending may be added. Not only the prediction of the state of bending after soldering (i.e. at "1 h") is reproduced by the calculation, but as well the relaxation behaviour during nearly 2000 h of storage at room temperature appears to be reasonably described by the present approach (*figure 4*). Creep data have been available for the solder alloy SnPb37Ag2 which obviously approximates the SnPb40Ag1 alloy well.

The stress-free state starts with the initial curvature at the time of solidification. For an elastic bi-material, each temperature defines a certain state of stress at a given radius of curvature.

When a non-elastic deformation such as creep of the solder layer takes place, the system tends to deform into the direction of a new stress-free state; therefore, the function describing curvature versus temperature shifts. Each step in temperature affects first the elastic bi-material response and second, the creep rate of the solder layer, i.e. the time necessary to relax a given state of stress. The higher the temperature, the shorter is the time to relax, but on the other hand, the smaller is the driving force, because the temperature comes closer to the starting point.

Figure 5 depicts some experimental and calculated results for DCBs with a small difference in size, soldered to a 5 mm Cu baseplate with the much more creep resistant solder alloy SnAg3.5. The curvature has been measured along straight lines on the back side of the module by a 3D measuring system, crossing the location of the DCBs centres. Data from approximately 20 samples were processed to give mean value and standard deviation of the local displacement, which is defined by the height difference between the DCBs centre displacement and the reference height given by two points at a certain distance from the centre. The reference height represents the unbent state of the module, here within a span of 20 mm.

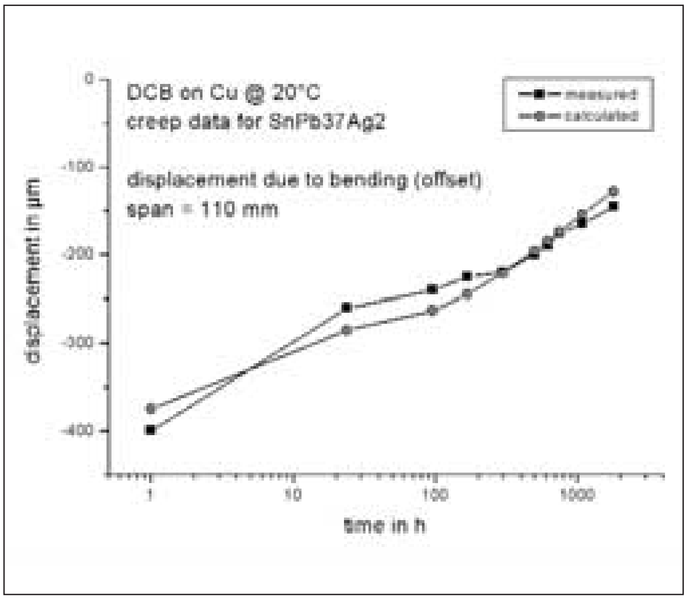

Figure 4:
Calculated relaxation behaviour of a Cu baseplate joined with a DCB substrate compared to the mean value of the measurements in figure 1; here, the displacement relative to the curvature before soldering is shown. The starting point taken arbitrarily at "1 h" relates to "after soldering".

Calculation of the simple elastic bending of the given composite geometry (*figure 5*) results in a local displacement of –13 µm, measured across a span of 20 mm, for cooling down from the solder alloys melting point to room temperature, i.e. ΔT = 200 K. This result is derived from the radius of curvature which is independent of the lateral DCB size. The result in *figure 5* shows that even with the creep resistant SnAg3.5 solder alloy, a large amount of relaxation occurs during cooling down after soldering and the manufacturing steps.

Creep of the solder layer reduces the theoretical elastic displacement of –13 µm (i.e. the elastic bending due to a ΔT of 200 K) to values between –6 and –8 µm, calculated for the given DCB sizes. The results in *figure 5* clearly show the size effect related with the solder joints' area: The smaller the DCB area, the larger, of course, is the shear stress compensating the bending force which only scales with the DCBs' length. The larger shear stress causes faster creep; therefore, the smaller the DCB, the less is the curvature (displacement) arising after a specified time.

While creep of SnAg3.5 during cooling down from soldering is described reasonably well (*figure 5*), a deviation is encountered during the long duration of room temperature creep. These differences between calculation and experiment are mainly attributed to the fact that the constitutive creep behaviour of SnAg3.5 has not been as well experimentally verified as e.g. the creep behaviour of eutectic SnPb alloys. Time to rupture data indicate the creep resistance of SnAg3.5 to be between one and two orders of magnitude better compared to pure Sn. The material properties used

	SnPbAg2	Pb	Sn
A1 [s-1]	9.62 x 104	2.2 x 108	9.0 x 105
A2 [MPa-1]	0.087	0.207	0.065
n [-]	3.3	7.0	5.5
Q [J mol-1]	67000	110800	72250

Table 1: *Material parameters of the constitutive creep behaviour taken from Winter, Wallach; Soldering and Surface Mount Technology 26 (1997) 61-64*

for the creep calculation here were taken to evaluate a creep rate of one order of magnitude lower than the creep rate of pure Sn (*table 1*); obviously, this is a conservative estimate (*figure 5*) because the creep resistance of SnAg3.5 is better than predicted.

Using the model proposed above, the effects of geometry (i.e. substrate size, layer thickness), material (i.e. Young's modulus, thermal expansion coefficient), and the creep behaviour of different solder alloys can be explained. The results show a strong effect of the substrate size, because the large area covered by the solder joint compared with the gap thickness is the reason that even small shear stresses encountered during creep of the solder layer give rise to strong bending forces on the composite.

In principle, the behaviour of the composite during temperature cycling can be addressed as well: using a given temperature-time profile, elastic bending will take place during the heating and cooling phase. It depends on the heating or cooling rate how much relaxation occurs while changing the temperature. While the temperature is changing, a mechanical strain rate is prescribed onto the solder layer. At the high temperature dwell time, relaxation will be fast compared to the low temperature range; thus, a stress-free state much closer to the high temperature setpoint will settle in, with an overlay of thermal and mechanical excursions. Stresses will of course be higher in the low temperature range.

The main advantage of the proposed modelling approach is that parameter variations can be evaluated without high computational effort. With the present model, the overall behaviour of bending of a "bi-metallic" composite is described well (*figures 4, 5*). Some further improvements are necessary to describe the fatigue behaviour of large area solder joints because the model does not take into account the stress/strain concentration close to the edges of the DCBs which are the sites of fast fatigue damage due to temperature cycling. ■

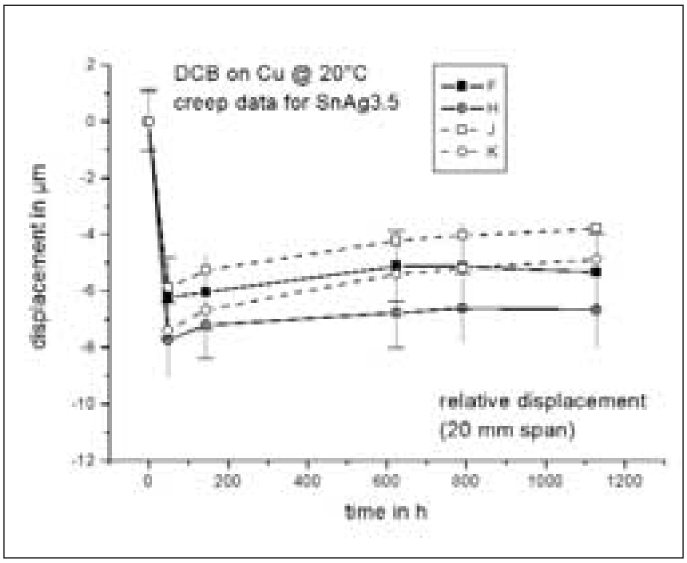

Figure 5:
Comparison of measured and calculated local curvatures of a composite of a DCB (0.3 mm Cu, 0.635 mm Al2O3, 0.3 mm Cu) soldered with SnAg3.5 on a 5 mm thick Cu baseplate. The difference between the initial displacement and the one after soldering and storage is displayed.

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