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Residual compression in area array packages induced by underfill shrinkage

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Abstract

A non-linear finite element model is developed to investigate underfill shrinkage as a possible source for obtaining beneficial residual compression in solder grid array interconnects. The axisymmetrical model geometry consists of a unit cell of concentric cylinders, the inner with properties representative of solder and the outer with properties representative of underfill, having an outer radius of half the array pitch. The solder, which is assumed to be eutectic, is modeled as an elastic–plastic material that exhibits creep behavior. The elastic modulus and Poisson's ratio of the underfill material, E_u and ν_u, as well as the percentage of unconstrained linear shrinkage, ϕ, are varied to determine the influence these parameters have on the final steady-state stresses in the solder connections. To represent the underfill materials in common use, E_u ranged from 0.5 to 8.0 GPa, ν_u ranged from 0.2 to 0.4, and ϕ ranged from 0.2% to 1.0%. Upon shrinkage of the underfill during curing, the model predicts that the interconnect initially experiences residual compression in the axial direction. Due to tension in the radial direction, however, creep strain causes the axial compressive stress to lessen until a state of hydrostatic stress is reached. For the underfill properties tested, all the residual, steady-state stresses were compressive. The magnitude of this compression is shown in graphical form as a function of E_u, ν_u, and ϕ. An analytical expression for estimating the magnitude of residual compression as a function of these underfill properties is also included. The potential effect of the residual compression on the fatigue life of a package is discussed in the context of a particular example.

1. Introduction

Solder interconnects in area array packages have been observed to fail in cyclic fatigue as a result of cracks propagating parallel to and near solder/pad interfaces. These cracks are initiated by the shearing of the connections caused by the thermal mismatch between the chip carrier and printed wiring board. Much research has centered on the development of fatigue life models used for the life prediction of joints experiencing this type of shearing fatigue [1]. Larson and Verges [2] have proposed a fracture-based fatigue life model that incorporates the addition of a compressive force normal to the crack face as a potential source for suppressing this failure mode. This compression could be induced through some mechanical clamping action or by the presence of underfill [3–5]. This paper addresses how

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one might achieve a beneficial amount residual compression by a judicious choice of underfill.

Underfills are polymers which are used to fill the volume between the solder interconnects. The use of underfill has been noted to provide certain benefits in package performance, however their use can significantly complicate a rework effort, should that be necessary [6]. Underfills are usually applied by placing a bead of liquid polymer around three edges of the chip carrier, or chip, of a pre-soldered package, with multiple line passes often necessary for large packages (>10 mm). The liquid wicks between the package and printed wiring board and subsequently cures to a solid. Typical materials possess a glass transition temperature in the neighborhood of 125 °C and act elastically at room temperature. It is common for the commercially available materials to exhibit unconstrained cure shrinkage of up to 3% in volume. This contraction, which acts to pull the package closer to the printed wiring board (PWB), is limited by the presence of the solder interconnects, thus possibly inducing a beneficial compression in the interconnects in the direction normal to the PWB (and corresponding tension in the underfill). However, underfill shrinkage may also induce interconnect tension in the transverse direction, i.e., parallel to the PWB. Since solder is a creeping material, one might expect the interconnects to inelastically strain in response to these residual stresses and reduce, or even eliminate, the potential benefit of the residual compression.

This work seeks to estimate the residual stresses induced in a solder grid array by an underfill that shrinks upon curing. The solution is made difficult by the complex geometry and the nonlinear visco-plastic response of the solder. In order to elucidate the important features of the problem and develop general relationships which may be applied by those engaged in designing packages, here we employ idealizations of the geometry and the material behavior in a nonlinear finite element model. The following section describes the unit cell geometry and the pertinent simplifying assumptions. Section 3 presents the detailed, non-linear finite element model for a geometry which is similar to many commonly used packages in actual components. The Section 4 presents the steady-state axial stresses in the interconnects as a function of the stiffness and Poisson's ratio of the underfill as well as the unconstrained linear shrinkage of the underfill upon curing. Finally, a description of how these steady-state stresses may affect the fatigue life of the package is offered in the conclusions.

2. Representative geometry

Individual solder interconnects in grid array packages, including ball grid arrays (BGA), flip chips (FC) and chip scale packages (CSP), which have resulted from cooling of a liquid phase will naturally take shapes which possess nearly constant mean curvature [7]. A variety of assumptions about shape have been made by those examining the mechanics of interconnects [8]. In order to minimize complexity in interpreting the results while revealing the primary effects that underfill has on the residual stresses in interconnects, here we adopt the assumption that each solder interconnect is cylindrical in shape, i.e., the variation in surface curvature of the interconnect is assumed to have little effect on the nominal axial stress, especially in the regions near the pads, where pad size dictates the radius of the interconnect. We further assume that a repeating unit cell representation is appropriate, i.e., each interconnect is part of an infinite array.

Accordingly, the outer boundary of the cell is constrained in the radial direction throughout the curing process, due to the symmetry of the array structure. The radius of the cell equals half the interconnect pitch. The symmetry of this repeating cell is clearly appropriate for interconnects in the interior of an array. The infinite array assumption yields a conservative estimate of the residual compression realized in interconnects located near the array edges. This is due to the constraint on radial displacement of the cell, which reduces the desired axial compression, being less at an array's periphery. The surfaces bridged by the interconnects, e.g., a chip carrier and printed wiring board, are taken to be much less compliant than the solder and underfill and are therefore constrained to remain planar (although the distance between them, the standoff height, is permitted to change).

3. Non-linear finite element model

In order to estimate the residual steady-state stresses resulting from the contraction of the underfill upon curing, a non-linear finite element model is solved using ABAQUS [9]. The finite element domain pictured in Fig. 1 is an axisymmetric slice of the concentric cylindrical unit cell described in the previous section, exploiting the symmetry about the horizontal mid-plane. The relative proportions of the geometry, e.g., the interconnect height, radius and pitch, are chosen to represent those commonly found in contemporary area array packages, including BGAs, flip-chips and chip scale packages. The particular values used are indicative of a typical BGA, i.e., the interconnect height is taken to be 0.5 mm, the pad radius is 0.4 mm, and the pitch is 1.27 mm. Referring to Fig. 1, the left-most boundary on the finite element domain coincides with the axis of symmetry, therefore, the nodes there are constrained from movement in the radial direction. The nodes on the right-most boundary, which lie on the outer edge of the underfill material, are constrained from movement in the radial direction as well. This constraint is in keeping with the