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Fatigue damage modeling in solder interconnects using a cohesive zone approach

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Abstract

The objective of this work is to model the fatigue damage process in a solder bump subjected to cyclic loading conditions. Fatigue damage is simulated using the cohesive zone methodology. Damage is assumed to occur at interfaces modeled through cohesive zones in the material, while the bulk material is assumed to be linear elastic. The state of damage at a cohesive zone is incorporated into the cohesive zone constitutive law by a elasticity-based damage variable. The gradual degradation of the solder material and the corresponding damage accumulation throughout the cycling process is accounted for by a damage evolution law which captures the main damage characteristics. The model prediction of the solder bump life-time is shown to be in good agreement with one of the commonly used empirical life-time prediction laws.

Keywords: Cohesive zone; Fatigue damage; Solder joint; Life-time

1. Introduction

In the electronics industry, reliability of an IC package is usually determined through the integrity of its solder joint interconnects. The latter have the function of providing both electrical and mechanical connections between the silicon chip and the printed circuit board. Repeated switching of the electronic device leads to temperature fluctuations which, combined with the mismatch of the coefficients of thermal expansion (CTE), will result in stresses causing fatigue of the solder joints. Progressive damage will eventually

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result in a device failure. This problem is becoming increasingly important as the flux of the dissipated energy in the solder joints is increasing due to miniaturization.

Numerical prediction of fatigue life-time of solder joints generally consists of four main steps. Firstly, a constitutive model which describes the solder material behavior is chosen. Secondly, one loading cycle is simulated using the finite element method (FEM), where the stresses and the strains in the material are calculated. Thirdly, from the calculated stresses and/or strains, the number of cycles to failure N_f is calculated based on a selected fatigue life prediction model. A review of such models can be found in Lee et al. (2000). Finally, the model prediction is verified using experimental thermal cycling data. This approach is the most popular among other existing approaches for fatigue analysis of solder joints. This is mainly due to its simplicity and relatively short computing time. However, there is a major drawback associated with this approach. The stresses and strains are calculated from a single loading cycle and the material properties of the solder are assumed to remain constant during the successive cycles. This assumption results in underestimated values of the fatigue life because in reality, repeated cycling results in a gradual degradation of the solder material (Basaran et al., 2001). This has been emphasized experimentally through the observation that creep hysteresis loops of solder materials collapse over the thermal cycles (Zhang et al., 2000). Moreover, solder joint fatigue models were developed based on experimental thermal cycling tests on macroscopic specimens. The applicability of such models to a solder joint has not yet been justified. More realistic models should account for the microstructural evolution of the solder material during the process of cycling. During thermal and/or mechanical cyclic loading, the solder material undergoes phase separation and severe coarsening at an early stage of the cycling process (Matin et al., 2003; Ubachs et al., 2003). The coarsening of the solder microstructure eventually leads to stress concentrations in the material which, in addition to the localization of the interfaces with the coarsened phases, will contribute severely to the fatigue damage. The incorporation of all such phenomena explicitly in a fatigue model is rather complicated. Instead, this can be achieved partially by adopting a continuum damage approach, for example, where the microstructural changes and the corresponding material degradation are accounted for in the constitutive material model itself by a damage variable. However, besides the requirement of extensive computations, the choice of a damage variable and a damage evolution law is quite arbitrary and experimental verifications are usually not available.

The cohesive zone method is a numerical tool for the mechanics of interfaces, that was initially developed to model crack initiation and growth. This method treats fracture as a gradual process in which separation between incipient material surfaces is resisted by cohesive tractions (Nguyen et al., 2001). It is a typical interfacial damage model, which can be situated between continuum damage mechanics and fracture mechanics. In comparison with fracture mechanics, the cohesive zone method has the advantages of smoothing the stress singularities at the crack tip and the easy adaptability to material and geometrical nonlinearities (Chaboche et al., 2001). Compared to continuum damage mechanics, the cohesive zone method can be used to model cracking at interfaces between dissimilar materials. The fracture characteristics of the material such as fracture energy (the area under the traction curve) and fracture strength (the peak cohesive traction) are included in a typical cohesive zone constitutive relation. Consequently, crack initiation and crack growth emerge as natural outcomes of the boundary value problem solution without any separate criteria. In the past decade, the cohesive zone method was mainly applied to model cracking under monotonic loading conditions (Abdul-Baqi, 2002; Chaboche et al., 2001; Tijssens, 2000; Xu and Needleman, 1993). The applicability of this method to fatigue damage under cyclic loading has only quite recently started to receive some attention (de Andres et al., 1999; Nguyen et al., 2001; Roe and Siegmund, 2003; Yang et al., 2000). Damage, as a dissipative mechanism, can be accounted for explicitly by incorporating a damage variable into the cohesive zone constitutive law (Roe and Siegmund, 2003). According to this approach the peak cohesive traction and cohesive energy are assumed to diminish with the damage parameter. The damage is determined using an evolution law in which the damage rate is a function of the cohesive parameters. An other way to account for damage is to include an unloading–reloading hysteresis into