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Direct simulation of fatigue failure in solder joints during cyclic shear

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ABSTRACT

A numerical finite element analysis is undertaken to directly simulate failure of solder joint caused by cyclic shear deformation. In the model the tin (Sn)-silver (Ag)-copper (Cu) solder and two copper substrates constitute a lap-shear testing configuration. A progressive damage model is incorporated into the rate-dependent elastic-viscoplastic response of the solder alloy, resulting in the capability of simulating damage evolution and eventual failure through crack formation. The study concerns three different applied shear strain rates, 1, 10 and 100 s^{-1}, under both the monotonic and cyclic loading conditions. It is found that, in the reference case of monotonic loading, the strain at failure can be influenced significantly by the fracture path in the solder. There is a tendency for cracking to occur closer to the interface during cyclic loading. The initiation of fatigue cracks is generally insensitive to the applied strain rate. However, the total fatigue life, in terms of the number of cycles to final failure, is seen to decrease significantly in the case of highest strain rate.

1. Introduction

Fatigue failure of solder joints in microelectronic packages has always been a serious reliability concern [1–3]. Cyclic deformation of solder can be induced by the thermal expansion mismatch between the components (e.g., semiconductor chip, chip carrier, and/or printed circuit board) connected by the solder. In addition, solder joints may experience severe mechanical loading, such as vibrational fatigue, in many military and civilian applications. Damage can be generated by the excessive plastic deformation and/or creep inside the solder alloy, or by more brittle forms of failure along the thin intermetallic layer at the interfacial region of the joint. For engineering design purposes, it is of interest to develop numerical simulation capabilities which can quantitatively predict failure in solder.

Traditionally, numerical prediction of solder fatigue frequently involves empirical fatigue criteria to obtain the number of cycles to failure. This phenomenological approach may be of the Basquin type [4]

$$\frac{\Delta\sigma}{2} = \sigma_f'(2N_f)^b, \tag{1}$$

or, more commonly, of the Coffin-Manson type [5,6]

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_f)^c. \tag{2}$$

Here $\frac{\Delta\sigma}{2}$ is the stress amplitude, σ_f' is the fatigue strength coefficient, N_f is the number of cycles to failure, b is the fatigue strength exponent, $\frac{\Delta\varepsilon_p}{2}$ is the plastic strain amplitude, ε_f' is the fatigue ductility coefficient, and c is the fatigue ductility exponent. From a given finite element analysis, the maximum stress or plastic strain ranges in the solder joint can be obtained, which can then be substituted to Eqs. (1) or (2) to calculate the number of cycles to failure [7–12]. This approach has been useful, within a given numerical modeling framework, for assessing fatigue life of solder joints under different geometrical, material and loading conditions.

The general method described above, while indirect, is largely necessitated by the impracticality of simulating direct material failure in a realistic setting. However, since numerical methodologies exist for modeling damage and failure in ductile metals, the present study thus aims at incorporating failure into the finite element analysis and simulating fatigue performance of a model solder joint structure. We attempt to test the feasibility of applying this direct approach to address the solder fatigue problem.

The model utilizes a simple lap-shear test format, with the following salient features:

- A ductile damage model is built into the analysis, which, in conjunction with the element removal process in the explicit numerical scheme, is capable of simulating direct failure of the solder material.
- The rate-dependent response of a tin (Sn)-silver (Ag)-copper (Cu) solder is taken into account to specifically address the loading rate effect.

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