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Effect of geometric complexities and nonlinear material properties on interfacial crack behavior in electronic devices

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ABSTRACT

Interfacial failures are often found in solder joints between electronic components and PWAs, under shock and drop loading. These interfacial fractures are often either between layers of dissimilar intermetallic compounds (IMCs), or between the solder and IMC layer. Studies have revealed that these interfaces are usually scalloped (wavy and non-planar) and that the waviness decreases with continued thermal aging, accompanied by a reduction of the apparent resistance to interfacial crack initiation. This study investigates the effects of the interfacial waviness, nonlinear solder material properties, local geometric complexities, and the initial crack length, on the resistance to crack initiation. Most of the studies in this field until this point have been either simple theoretical models not including all complexities or few limited experimental work. A computational framework is generated here to comprehensively include all important parameters that can then make efficient predictions cost-effectively and provide insights on the dependency of the interfacial fracture properties on all these parameters. Accurate and efficient assessment of such fracture properties will inherently help in designing reliable electronic assemblies and prevention of premature field failures.

1. Introduction

Electronic assemblies rely on soldered connections between metallized terminals on components and matching terminals on printed wiring boards (PWBs). These joints are created by forming multiple species of metallurgical intermetallic compounds between the tin in the solder and the metallization on the pad. As an example, Cu_6Sn_5 and Cu_3Sn intermetallic layers are formed with copper solder pads, while SnCuNi intermetallics are formed with Nickel-plated solder pads. The interfaces between these intermetallic layers are wavy and scalloped, as are the interfaces with the solder. These (Fig. 1) interfaces are sometimes the weakest part of the structure, as the toughness of these brittle materials is low and the stresses can be high due to discontinuity of properties across these interfaces. Failure due to dynamic mechanical stresses, for example because of drop and shock events, is often by interfacial fracture.

Published literature [1,2] suggests that with continued thermal aging, the waviness of the solder intermetallic layers decreases. This aging is accompanied by a decrease in the effective fracture resistance at this interface, especially under dynamic loading. The loss of fracture resistance is, at least in part, due to increase in the stress intensity factor coming from the decrease in the waviness. Accurate predictions of interfacial failure rely heavily on determination of the fracture parameters that adequately characterize the state of stress at the debonded interface of interest, i.e., the stress intensity factors (K_I, K_{II}, K_{III}) and the strain energy release rate (G). The strain energy release rate of the crack depends on the waviness, phase angle of loading, and the properties of the materials that meet at the interface. According to the concept of fracture mechanics, cracks start propagating when the strain energy release rate exceeds a critical threshold value, termed the fracture toughness of the material/interface. However, the crack growth is detectable only when the interface reaches a fatigue threshold, after which it follows a power-law dependence on the stress intensity factors. Cracked IMC interfaces being a common real-life problem entails a systematic way of predicting such failures and the first step to that is able to determine the threshold itself. Shang et al. [2] first attempted experimentally to quantify it. This study further extends that by creating a computational framework that can be used to various other solder compositions under different aging processes, based on their effect on interfacial IMC morphology.

A detailed multi-scale, global–local, elastic–plastic finite element fracture simulation model is constructed and calibrated against the test data published in the literature (Shang et al., 1996 [2]) for 3 different roughness profiles on a soldered cantilever fracture specimen. The global model of the test specimen analyses the average stresses in the solder and the local finite element model extracts the energy release rate at the tips of cracks of various lengths at the wavy IMC interfaces. The energy release rates are averaged over a periodic length of the wavy interface to obtain

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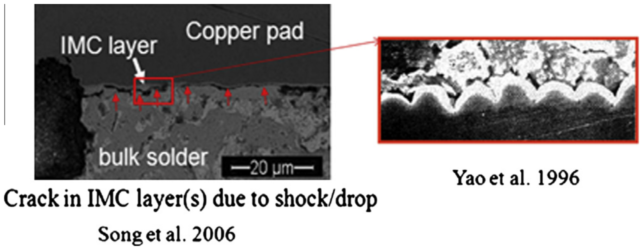

Fig. 1. Example of scalloped IMC layer in a solder joint.

effective average values, so that the results can be compared with test results reported by Yao and Shang. The initial crack length and loading rate are parametrically varied for each of the 3 roughness levels in Yao's paper. The analysis is repeated for elastic, elastic–plastic and viscoplastic solder properties. This study establishes a mutli-scale approach to build a FEA model with such complex geometry that can be used to perform detailed stress analysis at wavy interfaces of dissimilar materials [4]. This also provides fundamental insights into the effect of different parameters (interface roughness as characterized by statistical measures of the asperity profile and crack length) on solder-IMC interface fracture strength, through detailed micro-scale modeling of the IMC structure, under bending load. All the roughness features, properties and loading conditions are parameterized so that this model can be used for different cases.

2. Literature review

This section summarizes the important theoretical and experimental work done in interfacial fracture that is relevant to this problem. Numerous papers have been published on the mechanics of interfacial fracture. It started with closed-form analytical models from Rice, Suo and Hutchinson [5–7] which then got extended [4] for different loading conditions and mode mixity.

2.1. Theoretical models

Stresses near the crack tip at bimaterial interfaces have oscillatory behavior unlike those in the bulk. Rice [5] was the first to develop a mathematical expression for that behavior which essentially implies that the material in a small zone behind the crack tip will interpenetrate even when the crack is subjected to far-field tensile loads. Suo and Hutchinson [6] provided a way to relate the bulk stress intensity factor to the interfacial stress intensity factor. This technique relies on Dundurs' parameters, characteristic length, and a non-dimensional parameter to represent the oscillatory stress field at the crack tip. Hutchinson and Suo [7] showed that under certain conditions, the oscillatory stress field can be neglected, thus de-coupling the mode I and II interfacial stress intensity factors.

However, many practical components have wavy interfaces. For example the IMC layers formed between copper plates and solder are often scalloped and wavy. The interfacial morphology evolves steadily with time, even at room temperature, due to ongoing diffusion between the plating materials, copper trace and solder [3,8]. Evans and Hutchinson [4] were the first to relate the effective energy release rate at a wavy interface to that at a planar interface, as shown in the following equation.

The major limitation of the above theories is that they are not valid in the presence of elastic–plastic deformations. Evans et al. [9] suggested that the total energy required for interfacial cracking is a combination of the roughness shielding parameter and plastic work dissipation. Wei and Hutchinson [10] proposed a unified model which combined the Suo Shih Varias (SSV) model by Suo et al. [11] and embedded process zone model (EPZ) by Tvergaard and Hutchinson [12]. The model predicts that as peak stress increases for a fixed value of G, the interfacial toughening due to plasticity increases. Lane et al. [13] and Wei and Hutchinson [14] defined the criteria for limiting conditions of interfacial toughening due to plasticity at the elastic/plastic interface. However, the effect of aging on the contribution of interface adhesion and plastic work to fracture of wavy interface is still not well understood.

Evans and Hutchinson [4] investigated the effects of non-planarity on interfacial fracture. Their model is based on a bimaterial elastic interface which consists of a kink along a crack surface. When the crack surfaces contact at the kink, the stress intensities at the crack front differ from the applied values to an extent governed by the kink angle, the kink amplitude and the friction coefficient. The contacts resist the motion of the crack surface by means of friction and locking and thereby modify the energy release rate at the crack front. The modified strain energy release rate governs the effect of the contacting facets on the overall interface fracture resistance [4]. The mathematical model for predicting the effective stress intensity factors for non-planar interfaces is given by:

$$K_2^t + iK_1^t = K_2 + iK_1 - f(\xi)e^{i\omega}(K_1 \mathrm{Sin}\,\theta + K_2 \mathrm{Cos}\,\theta) \qquad (1)$$

where ξ is the size of the characteristic length on the crack surface, $f(\xi)$ is a non-dimensional scaling factor for the stress intensity factors, K_i^t is the stress intensity factor of the non-planar interface at the ith mode and θ is the facet angle of the non-planar interface. Because of the coupled nature of the stress intensity factors at the interfaces, usually strain energy release rate is a preferred mode of expressing the fracture properties. Thus, according to this derivation, the crack shielding due to the waviness of the non-planar interface decreases the stress intensity factor at the crack tip. The strain energy release rate of the crack depends on the waviness, phase angle of loading, and the properties of the materials that make up the interface.

2.2. Effect of aging on roughness

One of the most common wavy interfaces in electronic devices is at the IMC layers formed between copper and solder. These interfaces thicken and weaken with aging. Yao and Shang [2], Luhua and Pang [1], Song et al. [3], Jang et al. [15], Tu et al. [8] have reported this. Fig. 2 shows the variation in the morphology of Cu_6Sn_5/Cu_3Sn interface of a SnAgCu interconnect with Organic Solderability Preservative (OSP) finish, at various conditions of thermal cycling [16].

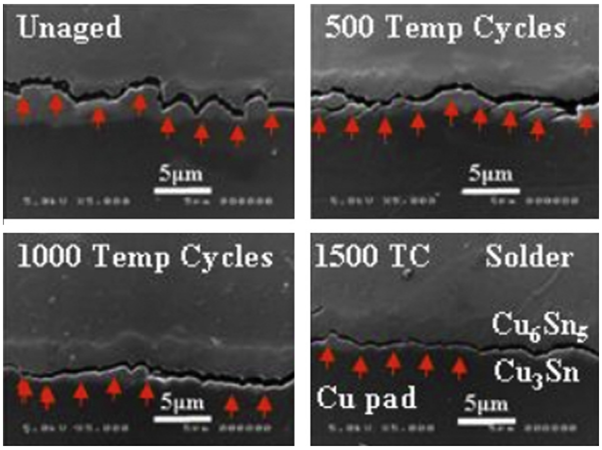

Fig. 2. Changes in interface morphology due to aging [3].