Finite-Element Simulation of Stress Intensity Factors in Solder Joint Intermetallic Compounds

M. O. Alam, Hua Lu, Chris Bailey, and Y. C. Chan

Abstract—The trend toward the miniaturization of electronic products leads to the need for very small sized solder joints, where the volume fraction of intermetallic compounds (IMCs) would be higher. In this paper, a fracture mechanics study of the IMC layer for SnPb and Pb-free solder joints has been carried out using a finite-element numerical computer modeling method. It is assumed that only one crack is present in the IMC layer. The linear elastic fracture mechanics approach is used for the parametric study of the stress intensity factors (SIFs) for SnPb and Pb-free solder joints at the predefined crack in the IMC layer of the solder-butt-joint tensile sample. Contrary to intuition, it is revealed that a thicker IMC layer, in fact, increases the reliability of a solder joint for a cracked IMC—assuming that there is only a single crack that exists in the IMC layer. Even if the whole solder layer is replaced by the IMC in the solder joint, the fracture propagation possibility is greatly reduced. Values of $K_I$ and $K_{II}$ are found to decrease with the location of the crack farther away from the solder interfaces while other parameters are constant. Temperature and strain rate are also found to have a significant influence on the SIF values. It has been found that a soft solder matrix generates a nonuniform plastic deformation across the solder–IMC interface near the crack tip that is responsible for obtaining a wide range of $K_I$ and $K_{II}$ values.

Index Terms—Failure analysis, finite element modeling, fracture mechanics, intermetallic compound, reliability, solder joint.

I. INTRODUCTION

The demand for Pb-free solders in a green environment and the increasing requirements for high-density interconnection technology to miniaturize electronic goods are the two most critical considerations in the global electronics market. Such a twofold critical requirement possesses a reliability threat in the selection of proper materials and processes as a state-of-the-art requirement of the electronics industries. Eutectic Sn–Pb solders have long been used due to the advantages of their mechanical properties, low melting temperatures, and excellent wetting properties. In response to the concern over Pb used in electronic assemblies, much work is ongoing over the last few years to find an acceptable Pb-free solder for various electronic attachment applications. Of all the Pb-free solders, Sn-based solders are the most attractive materials for the replacement of conventional Sn–Pb solders [1].

During the soldering process, the formation of intermetallic compounds (IMCs) between Sn-containing solders and substrates is inevitable [1]–[4]. Typically, a Cu substrate is used as a wettable metallization pad in electronic soldering applications. Interaction and interdiffusion behaviors between the solder and the Cu base metal have been intensively studied. It is now known that, at the Cu/solder interface, Sn reacts rapidly with Cu to form Cu$_2$Sn$_3$ IMCs during reflow soldering which grow over the subsequent aging period. It has been reported that the strength of the solder joint decreases with an increasing thickness of IMCs formed at the interface, and therefore, the IMC has been believed as an initiation site for microcracks [5]. Depending on the IMC thickness and the different layers of IMCs at the interface as well as the location of the first critical crack, a fracture either propagates through the IMC layers or switches from IMC to solder and, again, from solder to IMC [6]–[8]. In fact, a stress singularity might always exist at the interface of the IMC and solder due to the asymmetry in their elastic and plastic properties. This stress singularity tends to exhibit higher stress intensity factors (SIFs) and mode mixity at the tip of a crack in the IMC layer as compared with equivalent cracks in homogenous materials.

There have been extensive theoretical and experimental works carried out on the subject of stress singularity and the fracture initiation criterion for bonded joints of brittle and ductile materials at their interface [9]–[13]. Investigations on the cracking near the interface of ceramic–metal bonding reveal that cracks in the ceramic region deflected toward the ductile metal layer; however, they switch back again to the brittle layer, forming a zig-zag fracture path similar to that observed at the solder interface. A fracture mechanics approach was used for those theoretical studies. An in-depth understanding of the fracture path at the solder interface demands a similar approach. Moreover, because of the viscoplastic properties of solder alloys, cracks inside the IMC layer experience a complicated compliance-mismatch-dependent stress concentration that was not studied much.

Therefore, this paper addresses the effect of different solder alloys [such as SnPb and SnAgCu (SAC)], location of the crack, solder joint thickness, temperature, and strain rates on the quantitative investigation of crack propagation propensity near the solder interface. This explores the linear elastic fracture mechanics (LEFM) approach by measuring SIFs (such as $K_I$, $K_{II}$, and crack angle deflection $\theta$) for each condition.
II. NUMERICAL METHOD

A. Model for FE Analysis

A tensile specimen of the butt joint of the solder alloy sandwiched between two copper plates is considered for this study. It is assumed that 2–11-μm-thick IMC layers are formed at the solder–copper substrate interfaces. Therefore, four parallel interfaces such as copper–IMC, IMC–solder, solder–IMC, and IMC–copper are available in the specimen as shown in Fig. 1. A crack of 10-μm depth from the left edge and parallel to the interface is considered to be situated within one of the IMC layers. It is worth mentioning here that, for the sake of simplicity, only one crack of 10 μm in size was considered in this study while real solder joints might contain more cracks with different sizes. The location of the crack from the interface is varied from 1 to 10 μm. Thickness of the solder layer is also varied from 0.3 to 1 mm. Specimens are modeled in 2-D under plain strain conditions. A finite-element (FE) analysis has been conducted using a commercial FE software package ANSYS-11.

B. Material Model

In the computational model, Cu and IMC layers are considered to be isotropic linear elastic, whereas the solder material is considered to be a viscoplastic material. Table I lists the material properties of Cu, IMC, Pb-free SAC, and SnPb used in the FEM analysis.

To capture the viscoplastic material model of the solder alloys, the Anand model has been used through the ANSYS FE code. Previously, a specific viscoplastic constitutive law was needed to define as a user-defined subroutine code to represent the nonlinear rate-dependent stress–strain relations in some FE programs; however, recent versions of ANSYS incorporated a well-accepted rate-dependent phenomenological model that was first proposed by Anand. Anand’s constitutive model considers large isotropic viscoplastic deformations and small elastic deformations. There are two main features in the Anand model [14], [15].

1) There was no explicit yield condition and no loading/unloading criterion.

2) A single scalar, the deformation resistance $s$, is employed as an internal variable to represent the averaged isotropic resistance to the macroscopic plastic flow that arose from strengthening mechanisms such as dislocation filing up, etc.

The values of the Anand’s constant for SnPb and SAC solders shown in Table II were extracted from [15]. The solder joints’ part of the tensile butt-joint sample was meshed using the viscoplastic element of ANSYS, which is VISCO108, along with the values of the material parameters of Anand’s constant.

C. Numerical Methods for SIF Evaluation

SIFs such as $K_I$ (for tensile mode) and $K_{II}$ (for shear mode) play a major role in LEFM analyses. Many numerical methods using FE analysis have been developed to obtain the SIFs along a pre-existing crack front. The most common method of SIF calculation is the extrapolation of the displacements in the vicinity of the crack tip and uses the analytical expressions given by the LEFM [16]. ANSYS v.11’s LEFM fracture mechanics macro was used to compute the SIFs for this paper.

As the stresses and strains are singular at the crack tip, varying as $1/r^{1/2}$, singular FEs with the midside nodes shifted to the quarter point (see Fig. 2) introduced by Barsoum are usually adapted in the FEA to improve the numerical results in the vicinity of the crack tip [17]. Elements are initially generated circumferentially about and radially away from the keypoint (i.e., the crack tip) as shown in Figs. 1 and 2.

The SIF associated with the fracture toughness of the material is called the critical SIF $K_{IC}$, where $K_{IC}$ is material dependent. The $K_{IC}$ of a material can be obtained only by experiment. However, it is commonly used to compare with the structural SIF to determine the critical load as well as the critical crack size (in any engineering design, $K$ should not exceed $K_{IC}$). Therefore, in this paper, we used the $K_{IC}$ of the IMC reported from other experimental scientists to compare with our computed SIF values.
<table>
<thead>
<tr>
<th>Ansys constant</th>
<th>Materials parameters</th>
<th>Definition</th>
<th>SnPb</th>
<th>SnAgCu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$S_0$</td>
<td>initial value of deformation resistance</td>
<td>56.33</td>
<td>39.09</td>
</tr>
<tr>
<td>2</td>
<td>$Q/k (1/K)$</td>
<td>Activation Energy / Boltzmann’s Constant</td>
<td>10830</td>
<td>8930</td>
</tr>
<tr>
<td>3</td>
<td>$A (1/sec)$</td>
<td>pre-exponential factor</td>
<td>1.49e7</td>
<td>2.23e4</td>
</tr>
<tr>
<td>4</td>
<td>$\xi$</td>
<td>multiplier of stress</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>$m$</td>
<td>stain rate sensitivity of stress</td>
<td>0.303</td>
<td>0.182</td>
</tr>
<tr>
<td>6</td>
<td>$h_s (psi)$</td>
<td>hardening constant</td>
<td>2640.75</td>
<td>3321.15</td>
</tr>
<tr>
<td>7</td>
<td>$s’ (psi)$</td>
<td>coefficient for deformation resistance saturation value</td>
<td>80.42</td>
<td>1.7381</td>
</tr>
<tr>
<td>8</td>
<td>$n$</td>
<td>Strain rate sensitivity of saturation (deformation resistance) value</td>
<td>0.023</td>
<td>0.018</td>
</tr>
<tr>
<td>9</td>
<td>$a$</td>
<td>Strain rate sensitivity of hardening</td>
<td>1.34</td>
<td>1.82</td>
</tr>
</tbody>
</table>

**III. Results and Discussion**

Fig. 2 shows the SIF values of the IMC layers of the solder-butt-joint tensile samples with the joint where the solder material is replaced by the elastic IMC materials. A constant loading rate (0.8 MPa/s) was used at 25 °C while the joint thickness was ~1 mm. The location of the crack was 1 μm away from the solder–IMC interface. The loading rate, temperature, location of the crack from the solder interface, and solder thickness were found to have significant effects on the SIF values that will be described in the following sections. The curves in Fig. 3 also show the relationship between SIFs ($K_I$ and $K_{II}$) for SAC and SnPb solder. In a tensile sample of the solder joint where solder materials are replaced by IMC, $K_I$ values increase linearly with the applied load, whereas the presence of solder alloys has made significant changes in SIF values—$K_I$ values increase abruptly and show a peak value around 80 MPa. This numerical finding suggests that the fracture strength of solder-butt-joint tensile samples shall be around 80 MPa. In fact, several experimental findings reported earlier in [5]–[7] revealed fracture strengths of 86, 77, and 83 MPa, respectively. Although their experimental conditions differ to some extent, there is a reasonable agreement in the experimental fracture strength value of around 80 MPa. The range of loading rates, cross section of the solder joint, and joint thickness of the experimental works lay within the limit of the assumed values of the present FEA work. Therefore, FEA results of the fracture strength of the solder-butt-joint tensile samples of this work coincide with the findings from experimental works.

For a tensile sample of homogenous elastic materials, the following analytical solution can be used to measure SIF [18]:

$$K_I = C_1\sigma_{yy}\sqrt{\pi a}.$$  

$C_1$ is a constant that varies with the specimen and crack location. For a specimen of “Semi-infinite Plate with an Edge Through Crack under Tension,” $C_1 = 1.12$ [18]. Considering the similarity of the specimen studied in this research, the same value of $C_1$ is assumed. $a$ is the crack length, and $\sigma_{yy}$ is the applied stress. Throughout the simulation, we assumed a 10-μm-sized crack in the IMC layer. If we put $a = 10 \times 10^{-6}$ m and...
\[ \sigma_{xy} = 80 \text{ MPa}, \] 
we analytically find \( K_I = 0.503 \text{ MPa} \cdot \text{m}^{0.5} \) when the whole body is elastic. Numerically, by using ANSYS for the same model, we have found \( K_I = 0.51 \text{ MPa} \cdot \text{m}^{0.5} \)—considering the whole solder layer is replaced by the IMC. The slight difference between the analytical and numerical models is due to the elastic property differences between the IMC and the Cu that were not considered in the analytical model. It is worthwhile to mention that, in the present model of tensile solder-butt joints, the IMC layer is very thin compared with the Cu and solder layers. Therefore, the elastic property difference between IMC and Cu does not have any significant impact on the \( K_I \) value of tensile solder-butt joints.

From the experimental findings in [19]–[21], it was found that the critical value for the fracture toughness \( (K_{IC}) \) of the CuSn5 IMC ranges from 1.4 to 3 MPa \cdot \text{m}^{0.5}. Therefore, in a tensile sample of IMC-butt joints (where the solder is replaced by IMC), a crack will not propagate under \( \sigma = 80 \text{ MPa} \) when the crack size \( a = 10 \mu\text{m} \). However, in the present numerical analysis of solder joints, the \( K_I \) value of IMC exceeds the critical value of 1.4 MPa \cdot \text{m}^{0.5} for the same loading stress \( \sigma \) and the same crack size \( a \). It is clear that the presence of solder alloys at the interface changes the local stress–strain distribution near the crack tip.

While \( K_I \) is related to the SIF for the opening mode fracture solely due to tensile loading, \( K_{II} \) is related to the shearing mode fracture originated by shear loading as follows:

\[ K_{II} = C_2 \sigma_{xy} \sqrt{\pi a}. \]

Although \( K_{II} \) is negligible for a homogenous elastic material under uniaxial tensile loading, we have found a significant contribution by the \( K_{II} \) value in our numerical analysis that is sometimes higher than the \( K_I \) values (see Fig. 4). Fig. 4 shows the \( K_{II} \) value of the crack that is located within a 1-\( \mu \text{m} \) distance from the IMC–solder interface to that of the 10-\( \mu \text{m} \) distance. This is believed to be the presence of highly viscoelastic solder materials in our specimen. Solder materials between the Cu plates elongate viscoelastically with the applied load and time. Therefore, similar to the case of Poisson contraction, solder alloys contract in the other direction. This generates a strong shear contraction near the interface that contributes to the shear stress \( \sigma_{xy} \) in the IMC–solder interface and is responsible for the higher \( K_{II} \) value at the IMC crack tip. The crack near the interface is much affected by this Poisson contraction.

Both of these \( K_I \) and \( K_{II} \) values varied with the following:

1) alloy composition, i.e., material properties of solder alloys;
2) location of the crack, i.e., distance from the IMC–solder interface;
3) strain rate, i.e., loading rate;
4) solder temperature (room temperature lies above 0.5\( T_m \));
5) solder joint thickness, i.e., volume of the solder materials within the joint.

The effect of all these factors are described as follows where it is seen that the distance from the interface has been found to be much more sensitive.

### A. Effect of Crack Locations Relative to the Interface

To understand the influence of the solder alloy on the crack position near the interface and farther away, the same size of cracks were considered at a distance of 1, 2, 5, and 10\( \mu\text{m} \) from the IMC–solder interface. An applied load of 80 MPa and a loading rate of 0.8 MPa/s were used for both SAC and SnPb solder joints. Fig. 5 shows the variation of \( K_I \) and \( K_{II} \) values with the crack location (i.e., the distance between the crack and the IMC–solder interface). It is clear from the figure that SIF values increase sharply while the crack location approaches near the interface; in particular, the \( K_{II} \) value, i.e., the SIF of the shear mode increases from an insignificant value to a very high value that could lead to a very unstable crack. Fig. 4, shown in the earlier section, also reveals how the variations of \( K_I \) and \( K_{II} \) values are related to the applied loading and crack location. A loading beyond 60 MPa starts to contribute higher \( K_{II} \) values for the crack located 1-\( \mu\text{m} \) distance from the IMC–solder interface. Whereas there is no significant increase noticed in the \( K_{II} \) values for the crack located 10-\( \mu\text{m} \) distance from the IMC–solder interface.
Fig. 6. Von Mises stress distribution (in megapascals) at the crack tips as well as crack openings for the crack positions of (a) 1 and (b) 2 μm from the IMC–Pb-free solder interface (solder layer thickness is 1 mm, temperature is 25 °C (298 K), and loading rate is 0.8 MPa/s).

A Pb-free solder (SAC) contributes higher values compared to the SnPb solder for the crack located at a 1-μm distance from the IMC–solder interface. It is seen that cracks within 5-μm distance from the interface exert more than 1.5 MPa·m$^{0.5}$—a higher value than the experimental $K_{ic}$ values of IMC that could lead to fracture near the interface. Among the $K_I$ and $K_{II}$ values, $K_{II}$ values were found to be very sensitive to the crack location, particularly for the Pb-free solder. The effect of the thickness of the IMC layer was also studied where the crack location was considered at the middle of the IMC layer. The IMC layers of 2, 4, 10, and 20 μm having a crack at the middle had results that were nearly the same SIF values as shown in Fig. 5 for crack distances of 1, 2, 5, and 10 μm, respectively. Therefore, we concluded that thinner IMC layers have strong effects on the SIF—leading to unstable cracks.

Fig. 6 shows the von Mises stress distribution at the crack tips as well as crack openings for the cracks within (a) 1- and (b) 2-μm distances. Comparative crack opening displacements are clearly visible depending on the location of the crack from the interfaces. The simulation results from this work also agree qualitatively with the results of other simulations carried out by Tilbrook et al. [22] who conducted a study on the effects...
of plastic yielding on crack propagations near ductile/brittle interfaces of Cu/W. They used the term, “antisheilding” to express SIF amplifications due to the compliance mismatch between the elastic/plastic properties of ductile (Cu) and brittle (W) materials. While Tilbrook et al. considered relatively larger samples with high-strength material combinations, this paper dealt with small-sized samples and soft solder alloys. Therefore, the effect of compliance mismatch due to the viscoplastic deformation of soft solders has been noticed within only a few micrometers of distance from the IMC–solder interface.

Along with the $K_I$ and $K_{II}$ values, the direction of crack path $\theta$ is also an important fracture mechanics parameter that is used to predict the crack propagation direction. This is also known as “kink angle.” There are several methods to measure $\theta$. Among them, the maximum circumferential stress theory is widely used to compute $\theta$ [23]

$$K_I \sin \theta + K_{II}(3 \cos \theta - 1) = 0$$

$$\theta = 2 \tan^{-1} \left( \frac{1}{4} \frac{K_I}{K_{II}} \pm \frac{1}{4} \sqrt{\left( \frac{K_I}{K_{II}} \right)^2 + 8} \right).$$

For the pure Mode I, $K_{II} = 0$ yields $\theta = 0^\circ$, i.e., the crack propagates in a straight line perpendicular to face, whereas, for Mode II, $K_I = 0$ yields $\theta = \pm 70.5^\circ$. Therefore, for the mixed-mode case, the crack propagates within $0^\circ$ to $\pm 70.5^\circ$.

Fig. 7 shows the variation of the kink angle $\theta$ with the crack location for the present model. It is clear from the curves that the crack near the solder interface deviates to the solder region at a higher degree than that of the crack at a farther distance from the interface—obviously, the kink angle increases with the applied load. However, after reaching a peak, the kink angle again decreases with the applied loading. At a higher stress with a specific loading rate, solder alloys have opportunities for stress relaxation that reduces stress field around the crack tip. In fact, if fracture toughness reaches the critical value, the fracture propagates before we see any decrease in the kink angle. For the crack near the interface, the peak value of the kink angle was found at around 80 MPa—that is the typical fracture strength of solder joints found both from the current FE analysis and the previous experimental work.

Fig. 8. Relationship of crack deflection angle $\theta$ with the applied stress and crack positions from the IMC–Pb-free solder interface (solder layer thickness is 1 mm, temperature is 25 $^\circ$C (298 K), and loading rate is 0.8 MPa/s).

![Fig. 7. Relationship of crack deflection angle $\theta$ with the applied stress and crack positions from the IMC–Pb-free solder interface (solder layer thickness is 1 mm, temperature is 25 $^\circ$C (298 K), and loading rate is 0.8 MPa/s).](image)

![Fig. 8. Effect of loading rate (in megapascals per second) on SIF values at the IMC crack tip for (a) SAC and (b) SnPb solders at 25 $^\circ$C (298 K) and 75 $^\circ$C (348 K) while solder thickness is 0.5 mm and applied loading is 80 MPa. The location of the crack is 1 $\mu$m away from the solder–IMC interface.](image)
room temperature (25 °C), the peaks of SIF curves are shifted to higher loading rates for the temperature of 75 °C. The values of the peak are also lower for higher temperatures. Similar to the reasons aforementioned, solder alloys easily deform at a high temperature without generating significant stress at the solder–IMC interface region, and therefore, less SIF values are noticeable at the crack tip.

It is worth mentioning that, at a very slow loading rate, $K_I$ values were found well below 0.5 MPa·m$^{0.5}$. From the stress distribution contour, it is revealed that the stress relaxation of the solder materials near the edge interface at prolonged loading time is responsible for the lower values of SIF at slow strain rates.

Fig. 9 shows the elemental deformation near the IMC–SAC solder interface at 75 °C. Fig. 9(a) is for the slow strain rate, which shows a significant deformation of the solder alloys at the interfaces near the crack, while no such extended deformation is visible for the high strain rate modeling shown in Fig. 9(b). As a result, we see a higher crack tip opening that contributes higher SIF values.

C. Effect of Solder Thicknesses

Without any solder alloys between the Cu plates, sandwiched by only elastic IMCs, the $K_I$ value lies within $\sim$0.5 MPa·m$^{0.5}$. Nevertheless, the SIF value increases (in some cases,
with the increasing solder layer thickness are considered to be related to the mass effect of solder alloys. A thicker solder layer exerts a higher total viscoelastic deformation that results in a higher compliance mismatch between neighboring IMC and solder layers and therefore contributes higher stress near the crack tip in the elastic IMC region. On the other hand, a thicker ductile layer allows more plastic strain buildup, given the loading rate is low enough. This is reflected by very low SIF values (below 0.51 MPa · m$^{0.5}$) at around 0.008 MPa/s, as shown in Fig. 11. The extent of the plastic strain field shown in Fig. 9(a) also confirms this plastic strain buildup to yield the lower SIF.

Fig. 10. Effect of solder layer thickness on the $K_I$ and $K_{II}$ values of Pb-free and SnPb solders. (The crack position on the IMC–solder interface is 1 μm, temperature is 25 °C (298 K), applied load is 80 MPa, and loading rate is 0.8 MPa/s).

Fig. 11. Comparison of the sharp changes of the $K_I$ and $K_{II}$ values of the samples having solder joint thicknesses of 1 mm to that of the 0.3-mm solder joint (of SAC alloy) with the variation of loading rate. (Crack position from the IMC–solder interface is 1 μm, temperature is 25 °C (298 K), and applied load is 80 MPa).

decreases) significantly with the presence of solder alloys—the thicker the solder layer, the higher the changes in SIF values. Fig. 10 shows the variation of the $K_I$ and $K_{II}$ values of Pb-free and SnPb solders with the solder layer thickness at a loading rate of 0.8 MPa/s for the crack located at a 1-μm distance from the IMC–solder interface. Here, the effect is more significant for the Pb-free solder. However, it should be mentioned that the difference between Pb-free and SnPb solders becomes insignificant for the cracks located farther away from the interface.

Fig. 11 shows the comparison of the sharp changes of the $K_I$ and $K_{II}$ values of the samples having solder joint thicknesses of 1 mm to that of the 0.3-mm solder joint with the variation of loading rate. The highest values of SIF (i.e., the peak values) are noticed in quite different loading rates—samples with a thinner solder layer need a very slow loading rate to generate a localized stress field that results in higher SIFs values. Yet, the highest values of SIFs for the thin solder joint are far below the samples with 1-mm-thick solder joints.

It is interesting to see an abrupt increase of SIF values at the loading rate of 0.08–0.1 MPa/s. Further study is underway to understand this phenomenon. In general, higher SIF values are noticed for thick solder joint samples. Higher values of SIF with the increasing solder layer thickness are considered to be related to the mass effect of solder alloys. A thicker solder layer exerts a higher total viscoelastic deformation that results in a higher compliance mismatch between neighboring IMC and solder layers and therefore contributes higher stress near the crack tip in the elastic IMC region. On the other hand, a thicker ductile layer allows more plastic strain buildup, given the loading rate is low enough. This is reflected by very low SIF values (below 0.51 MPa · m$^{0.5}$) at around 0.008 MPa/s, as shown in Fig. 11. The extent of the plastic strain field shown in Fig. 9(a) also confirms this plastic strain buildup to yield the lower SIF.

IV. CONCLUSION

This paper describes results from a systematic numerical simulation of the fracture mechanics parameters of an IMC crack in a tensile solder-butt joint. Although the crack size and the crack distribution inside the IMC layer in a real solder joint (as well as the loading condition) might vary within a wide range, the simplistic numerical results from this work show a good agreement of the fracture strength values of tensile solder-butt joints with the experimental findings from other solder researchers. The significant finding from this simulation is that the crack near the interface is found to be more prone to propagate and also deflect at a higher angle. The thicker solder layer was also found to have a detrimental effect on the fracture characteristics of the solder joints. For the crack positions near the IMC–solder interface, higher values of $K_I$ and $K_{II}$ in the solder joint of SAC than those of the SnPb solder are found. However, with the crack position farther away from the IMC–solder, there is no significant difference noticed between Pb-free and SnPb solder joints. The strain rate shows a complex behavior—the highest range of $K_I$ and $K_{II}$ values were found at different rates depending on the thickness of the solder layer, temperature, and the position of the crack from the IMC–solder interface. It has been concluded that a soft solder matrix generates a nonuniform plastic deformation across the IMC–solder interface that is responsible for the higher $K_I$ and $K_{II}$ values and relatively lower fracture toughness of solder joints.

REFERENCES

Peterson’s Stress Concentration Factors
W. D. Pilkey, R. S. Barsoum, “On the use of isoparametric finite elements in linear
M. T. Tilbrook, I. E. Remanis, K. Rozenburg, and M. Hoffman, “Effects of
R. J. Fields, R. R. Low, and G. K. Lucey, “Physical and mechanical

Hua Lu received the Master’s degree in condensed matter physics from Wuhan University, Wuhan, China, in 1988, and the Ph.D. degree in computational physics from the University of Edinburgh, Edinburgh, Scotland, in 1992.
He is a Reader (Associate Professor) in computational science with the School of Computing and Mathematical Sciences, University of Green-
wich, London, U.K. He has published more than 40 technical papers in journals. His current research interests include multiphysics computer modeling of electronic components, reliability prediction methods, and design and manufacturing optimization methods and applications.

Chris Bailey was born in London, U.K., in 1962. He received the B.Sc. degree in mathematics, statistics, and computing and the Ph.D. degree in computational mathematics from the University of Green-
He is currently a Professor of computational mechanics and reliability with the University of Greenwich, where he heads the Computational Me-
chanics and Reliability Research Group. His research interests include develop-
ment and use of software tools to predict the behavior and reliability of materials in manufacturing processes and end products.

Prof. Bailey is a Senior Member of the IEEE Components, Packaging, and Manufacturing Technology Society and a committee member of the U.K. Chapter of the International Microelectronics and Packaging Society (IMAPS-UK). He was also the local organizer of the 2007 International Con-
ference on Thermal, Mechanical and Multiphysics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE 2007) and the General Chair of the 2008 IEEE Electronics System-Integration Technology Conference (ESTC 2008).

Y. C. Chan received the B.Sc. degree in electrical engineering, the M.Sc. degree in materials science, and the Ph.D. degree in electrical engineering from Imperial College of Science and Technology, Uni-
After eight years of industrial experience, he joined the City University of Hong Kong (CityU), Kowloon, Hong Kong, in 1991. He is currently the Chair Professor of Electronic Engineering, the Di-
rector of the EPA Centre, and the Assistant Head for Applied Research and Industry Relations with the Department of Electronic Engineering, CityU. He is world renown in electronic product reliability and has had extensive industrial connections in the local electronics and manu-
facturing industry. He is currently engaged in a RoHS and WEEE research program at CityU, in conjunction with a number of local manufacturers and international research and technical organizations. He is also a member of the China RoHS working group implementing the relevant laws and technical
testing in China. He has widely consulted for various companies for RoHS testing and compliance, and closely worked with some European partners on the forthcoming REACH directives. He has given keynote speeches on RoHS compliance and homogeneous materials worldwide and is in the process of chief editing a series of RoHS books and coauthoring some specialist chapters for the manufacturing industry in China. He has authored or coauthored more than 200 scientific publications in peer-reviewed journals and more than 100 international conference proceeding papers. He has also co-edited three books. His current research interests include advanced electronic packaging and assemblies, failure analysis, and reliability engineering.

M. O. Alam received the B.Sc.Eng and M.Sc.Eng degrees in metallurgical engineering from Bangladesh University of Engineering and Technology, Dhaka, Bangladesh, in 1995 and 1997, respectively, and the Ph.D. degree in electronic packaging from the City University of Hong Kong, Kowloon, Hong Kong, in 2004.
He was with Bangladesh University of Engineering and Technology as a Lecturer and an Assistant Professor until 2000. He was awarded the Marie Curie Incoming Fellowship by the European Union and joined the University of Greenwich, London, U.K., where he worked on reliability modeling of Pb-free solder joints. Since the end of the fellowship, he has been continuing his work on reliability modeling as a part-time Senior Research Fellow with the University of Greenwich. He is also a Senior Reliability Engineer with Oxssensis Ltd., Rutherford Appleton Laboratory, Oxfordshire, U.K. Oxssensis develops and commercializes high-temperature (~1000 °C) multiparameter optical sensors. He has published more than 60 journal and confer-
ence proceeding papers on electronic packaging and materials engineering. His research interests include reliability and failure analysis of electronic/sensor packaging and high-temperature materials, Pb-free solders, thermomigration, and electromigration.

Chris Bailey is a Senior Member of the IEEE Components, Packaging, and Manufacturing Technology Society and a committee member of the U.K. Chapter of the International Microelectronics and Packaging Society (IMAPS-UK). He was also the local organizer of the 2007 International Conference on Thermal, Mechanical and Multiphysics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE 2007) and the General Chair of the 2008 IEEE Electronics System-Integration Technology Conference (ESTC 2008).

Y. C. Chan received the B.Sc. degree in electrical engineering, the M.Sc. degree in materials science, and the Ph.D. degree in electrical engineering from Imperial College of Science and Technology, University of London, London, U.K., in 1977, 1978, and 1983, respectively.
After eight years of industrial experience, he joined the City University of Hong Kong (CityU), Kowloon, Hong Kong, in 1991. He is currently the Chair Professor of Electronic Engineering, the Director of the EPA Centre, and the Assistant Head for Applied Research and Industry Relations with the Department of Electronic Engineering, CityU. He is world renown in electronic product reliability and has had extensive industrial connections in the local electronics and manufacturing industry. He is currently engaged in a RoHS and WEEE research program at CityU, in conjunction with a number of local manufacturers and international research and technical organizations. He is also a member of the China RoHS working group implementing the relevant laws and technical testing in China. He has widely consulted for various companies for RoHS testing and compliance, and closely worked with some European partners on the forthcoming REACH directives. He has given keynote speeches on RoHS compliance and homogeneous materials worldwide and is in the process of chief editing a series of RoHS books and coauthoring some specialist chapters for the manufacturing industry in China. He has authored or coauthored more than 200 scientific publications in peer-reviewed journals and more than 100 international conference proceeding papers. He has also co-edited three books. His current research interests include advanced electronic packaging and assemblies, failure analysis, and reliability engineering.