A Numerical Approach Towards the Correlation Between Ball Impact Test and Drop Reliability

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Abstract
The ball impact test is developed as a package-level measure for the board-level drop reliability of solder joints in the sense that it leads to fracturing of solder joints around the intermetallics, similar to that from a board-level drop test. In this paper, both board-level drop test and package-level ball impact test are examined numerically for solder joints of nine Sn-Ag-Cu solder compositions. Correlations between the drop reliability and characteristics of the impact force profile are sought.

1. Introduction
The adoption of stiffer and more brittle lead-free solder alloys [1] along with the prevalence of mobile electronic devices brings the need of characterizing solder joint reliability under dynamic loads. The common way to characterize the reliability of solder joints is through board-level tests. For board-level test vehicles subjected to mechanical loads of reasonably high strain rates, it is frequently observed that fracturing occurs around the interface between the solder joint and its bonding pads, where intermetallic compounds (IMCs) develop [2-8]. Therefore, characterization of the strength of IMC is crucial to the assessment of reliability of solder joints under a dynamic loading condition. However, each solder joint in a board-level test vehicle connects to two bonding pads on the package side as well as the test board side. Quite often geometric configurations and surface finishes of the two pads are distinct [7]. It is therefore fairly difficult to specify a loading condition that allows fracturing to occur dominantly around a preferred pad, at which the IMC strength is to be examined. Considering the high cost and long duration a board-level test takes, direct testing on a package-level solder joint that involves only a single pad meets the demand more efficiently and economically.

For a single package-level solder joint, the ball shear test that shears off the solder joint along the direction parallel to the pad is generally employed in the industry to evaluate the strength of the solder joint. This test is simple and convenient to implement. However, from both experiments and numerical analyses, it has been noted that a conventional low-strain-rate ball shear test with a crosshead speed slower than 0.1 mm/s seldom leads to fracturing of IMC [9]. The same situation also occurs when a number of solder joints on a board-level test vehicle are sheared off simultaneously [10]. Since a conventional ball shear test with a low shearing velocity is unable to reproduce the typical IMC fracturing failure mode encountered in a board-level drop test, it can be expected that there is hardly a chance for ball shear testing results to be correlated with the drop reliability.

Apparently, if a test equipment capable of evaluating the IMC strength is to be developed based on the configuration of the ball shear test, the shearing velocity must be greatly enhanced [1,11-14]. Meanwhile, the test apparatus must be carefully designed to suppress structural resonance in order to obtain reliable force or acceleration measurements [15]. A high sampling rate data acquisition system is also a necessity.

Efforts have been devoted to the empirical correlation between board-level drop reliability and characteristics of the impact force profile from the ball impact test (BIT) [14]. In this paper, both board-level drop test and package-level BIT are examined numerically. We consider different Sn-Ag-Cu solder joint compositions, namely, Sn-4Ag-0.5Cu (SAC405), Sn-3Ag-0.5Cu (SAC305), Sn-2.6Ag-0.6Cu (SAC266), Sn-1Ag-0.5Cu (SAC105), and Sn-Ag-Cu solder alloys doped with trace elements: Sn-Ag-Cu-Sb (SACSb), SACXY1, SACXY2, SACXY3, and SACXY4. Through numerical solutions, insights into the analytical correlation between the drop reliability and characteristics of the impact force profile are provided.

2. Board-level Drop Test
We consider a 10×10×0.8 mm3 thin-profile fine-pitch ball grid array (TFBGA) chip-scale package interconnected to a 132×77×1 mm3 standard 8-layer JEDEC drop test board. The package contains a 5.5×5.5×0.25 mm3 silicon die and a 0.26 mm thick substrate. The diameter and standoff of a solder joint are 0.35 mm and 0.21 mm, respectively. Openings of a solder joint on the package side and the test board side are 0.26 mm and 0.28 mm, respectively. The pitch between adjacent solder joints is 0.5 mm. The mounting scheme of packages on the test board is shown in Fig. 1, following JESD22-B111 [16]. The figure also depicts the quarter symmetry modeling region for the finite element analysis. We consider the layout for which only the package at the center of the test board, U8, is implemented.

![Fig. 1: Schematic of test board and modeling region](image-url)
Fig. 2 shows the finite element model of the board-level test vehicle around the package. The finite element model contains 50,127 linear hexahedral solid elements and 180,909 degrees of freedom. The structure of the solder joint is simplified in the way such that the two bonding pads are both neglected. The test vehicle is dropped with the package facing downward under JEDEC drop test condition B [16], for which a half-sine impact acceleration pulse with a peak acceleration of 1500 G and a pulse duration of 0.5 ms is prescribed. The transient analysis, which follows the support excitation scheme [17,18] and incorporates with the implicit time integration, is performed using ANSYS v. 10.0.

![Finite element mesh around the package](image)

Fig. 2: Finite element mesh around the package

Elastic properties of constituent components except for the solder alloy are presented in Table 1. Transversely isotropic material properties are assigned for the test board and the substrate, Table 2. In these tables, $E$ is the Young’s modulus, $\nu$ the Poisson’s ratio, $\rho$ the mass density, and $G$ the shear modulus. Note that $z$ denotes the out-of-plane direction while $x$ and $y$ refer to in-plane directions. Mass-weighted damping and stiffness-weighted damping of the test vehicle are assumed 0.08 and 0.0013, respectively.

### Table 1: Elastic properties of constituents

<table>
<thead>
<tr>
<th>Component</th>
<th>$E$ (GPa)</th>
<th>$\nu$</th>
<th>$\rho$ (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>Transversely isotropic</td>
<td>Transversely isotropic</td>
<td>1.91</td>
</tr>
<tr>
<td>Die</td>
<td>131</td>
<td>0.23</td>
<td>2.33</td>
</tr>
<tr>
<td>Compound</td>
<td>28</td>
<td>0.35</td>
<td>1.89</td>
</tr>
<tr>
<td>Test board</td>
<td>Transversely isotropic</td>
<td>Transversely isotropic</td>
<td>1.91</td>
</tr>
</tbody>
</table>

### Table 2: Transversely isotropic properties for test board and substrate

<table>
<thead>
<tr>
<th>Test board</th>
<th>$E_x$ ($E_y$)</th>
<th>$G_{xy}$ ($G_{yz}$)</th>
<th>$\nu_{xz}$</th>
<th>$\nu_{yz}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.1 ($E_y$)</td>
<td>6.82 ($G_{xy}$)</td>
<td>0.39</td>
<td>0.11</td>
</tr>
<tr>
<td>Substrate</td>
<td>16.8 ($E_y$)</td>
<td>7.59 ($G_{xy}$)</td>
<td>0.39</td>
<td>0.11</td>
</tr>
</tbody>
</table>

In this study, we compare Sn-Ag-Cu solder alloys, namely, SAC405, SAC305, SAC266, and SAC105, and Sn-Ag-Cu solder alloys dopped with trace elements, namely, SACSb, SACXY1, SACXY2, SACXY3, and SACXY4. Fig. 3 shows stress-strain curves for these solder alloys, obtained from quasi-static uniaxial tensile tests on $10 \times 60 \times 3$ mm³ dog-bone specimens at a strain rate of approximately $2 \times 10^4$ s⁻¹. We construct trilinear elastoplastic constitutive relationships for the solder alloys based on these curves. For all solder alloys, $\nu$ is 0.36 and $\rho$ is 7.44 g/cm³. Isotropic hardening is presumed.

![Stress-strain curves for solder alloys](image)

Fig. 3: Stress-strain curves for solder alloys

In reality, material properties of the solder alloy depend greatly on the process, test methodology, and specimen size. In this regard, the actual mechanical response of the solder joint is quite difficult to obtain. The strain rate effect is ignored in this study since it is particularly difficult to identify without proper experimental measurements. Moreover, as of now, there are no suitable rate-dependent constitutive relationships for lead-free solder alloys that suit JEDEC drop test conditions, for which the strain rate is up to around $10^2$ s⁻¹ [5].

We denote normal stress, shear stress, and equivalent plastic strain as $\sigma_n$, $\sigma_s$, and $\varepsilon_p$, respectively. Here $\sigma_n$ stands for the normal component whereas $\sigma_s$ the squared-root sum of the two shear components of the surface traction. Fig. 4 shows the most critical solder joint and the locations where maximum $\sigma_n$, $\sigma_s$, and $\varepsilon_p$ occur during the course of the drop impact.

![Locations of maximum $\sigma_n$, $\sigma_s$, and $\varepsilon_p$](image)

Fig. 4: Locations of maximum $\sigma_n$, $\sigma_s$, and $\varepsilon_p$
Table 3 summarizes maximum $\sigma_n$, $\sigma_s$, and $\varepsilon_p$ experienced on the package side of the most critical solder joint during the course of the drop impact.

<table>
<thead>
<tr>
<th>Solder alloy</th>
<th>$\sigma_n$ (MPa)</th>
<th>$\sigma_s$ (MPa)</th>
<th>$\varepsilon_p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC405</td>
<td>107.6</td>
<td>44.16</td>
<td>6.831</td>
</tr>
<tr>
<td>SAC305</td>
<td>102.0</td>
<td>44.44</td>
<td>7.577</td>
</tr>
<tr>
<td>SAC266</td>
<td>93.45</td>
<td>33.67</td>
<td>8.265</td>
</tr>
<tr>
<td>SAC105</td>
<td>76.34</td>
<td>28.53</td>
<td>11.075</td>
</tr>
<tr>
<td>SACXY1</td>
<td>100.1</td>
<td>37.51</td>
<td>7.530</td>
</tr>
<tr>
<td>SACXY2</td>
<td>92.25</td>
<td>40.90</td>
<td>8.860</td>
</tr>
<tr>
<td>SACXY3</td>
<td>102.5</td>
<td>45.27</td>
<td>7.570</td>
</tr>
<tr>
<td>SACXY4</td>
<td>96.44</td>
<td>43.15</td>
<td>8.360</td>
</tr>
<tr>
<td>SACSb</td>
<td>105.9</td>
<td>39.62</td>
<td>6.675</td>
</tr>
</tbody>
</table>

Fig. 5 shows stress loci of $\sigma_n$-$\sigma_s$ for different solder joint compositions at Point A, where maximum $\sigma_n$ occurs on the package side of the critical solder joint, from the onset of the drop impact to when the peak $\sigma_n$ occurs. Apparently, during the course of the drop impact, $\sigma_n$ is about 5.25 times greater than $\sigma_s$ at Point A.

3. Ball Impact Test

The numerical methodology that deals with transient fracturing of a package-level solder joint subjected to a displacement-controlled impact load has been developed by Yeh and coworkers [19-25]. In this study, we follow the same methodology to examine transient impact force responses of the solder joints with different solder compositions.

The physical model for BIT is shown in Fig. 6. A rigid pin moves horizontally from left to right and strikes on the package-level solder joint with a constant impact velocity, $V_i$. In this study, we assume $V_i = 1.4$ m/s. It has been realized that when the IMC strength is not great enough, different $V_i$ do not bring significantly different impact force responses [24].

Fig. 7 shows the three-dimensional symmetric finite element model for the test vehicle. For components other than the solder joint, linear hexahedral solid elements are applied. Since the solder joint is spherical, at the onset of impact, it experiences force concentration around the contact region with the pin, incurring large deformations. To avoid hourglassing, a numerically unstable feature particularly for linear hexahedral solid elements subjected to a concentrated force, linear tetrahedral elements are applied on the regions depicted in Fig. 7. We neglect IMC in the numerical model since it is too thin to be implemented [24]. The transient analysis is performed using ANSYS/LS-DYNA v. 970.

Fracturing of the test vehicle can be categorized into two different types: fracturing within the solder alloy and interfacial fracturing between solder alloy and pad, at which IMC develops. Adequate fracturing mechanisms and corresponding failure criteria are therefore required to characterize the path of fracture propagation subjected to an impact load. Considering that fracturing within the solder alloy is a failure mode secondary to IMC fracturing during drop impacts [5-8], in this study, we focus on interfacial IMC fracturing of the package-level solder joint only.

Interfacial IMC fracturing is modeled using the tiebreak nodes-to-surface contact [24], which links adjacent meshes and confines the movements of nodes until the bond breaks. The bond failure is characterized by
\[
\left(\frac{f_n}{S_n}\right)^{\frac{n}{2}} + \left(\frac{f_s}{S_s}\right)^{\frac{s}{2}} \geq 1
\]  

(1)

where the subscripts \(n\) and \(s\) denote normal and shear, respectively, and \(f\) and \(S\) the weld force and the ultimate force when the bond breaks, respectively. In this study, an elliptical failure envelope, \(C_n = C_s = 2\), is adopted. Moreover, the shear strength of IMC is assumed to be two times greater than the normal strength of IMC. That is, \(S_s = 2\sigma_0A_e\), in which \(A_e\) is the equivalent area of the contact element while \(\sigma_0\) the tensile IMC strength in terms of the stress. Note that this merely represents an assumption and requires further experimental work to justify.

Characteristics of the impact force profile can be defined according to Fig. 8. Since the post-failure structural behavior of the solder joint is extremely complicated and hardly reproducible, we consider only the ascending part of the primary peak of the impact force profile, which stands for the structural behavior of the solder joint from the initiation of the impact load till fracturing starts.

![Fig. 8: Typical impact force profile](image)

1. \(F_{\text{max}}\): The maximum impact force, or the impact resistance, which relates to the IMC strength.
2. \(\tau_i\): The duration of the ascending part of the impact force profile, which stands for the ductility, \(d_i\), of the solder joint. If \(V_i\) varies insignificantly during the entire impact process, we have \(d_i = V_i\times\tau_i\), which also stands for the stroke from the onset of the impact till fracturing starts.
3. \(A_i\): The area below the ascending part of the impact force profile, which represents the toughness of the solder joint. This quantity is proportional to the impact energy exerted during the ascending part, \(E_i\). If \(V_i\) varies insignificantly during the entire impact process, we have \(E_i = V_i\timesA_i\).
4. \(S_i\): The slope of the ascending part of the impact force profile. If \(V_i\) varies insignificantly during the entire impact process, we have \(S_i = V_i\timesK_i\), where \(K_i\) stands for the equivalent stiffness of the solder joint.

Figs. 9, 10, and 11 show \(F_{\text{max}}\), \(E_i\), and \(d_i\) with respect to \(\sigma_0\), respectively, for different solder alloys.

![Fig. 9: \(F_{\text{max}}\) with respect to \(\sigma_0\)](image)

![Fig. 10: \(E_i\) with respect to \(\sigma_0\)](image)

![Fig. 11: \(d_i\) with respect to \(\sigma_0\)](image)
Fig. 12 shows stress loci of $f_n$-$f_s$ at Point A for different solder joint compositions during BIT. It is clear that the slope is approximately 1.23 and is nearly independent of solder compositions.

Comparing between stress loci at Point A induced by the board-level drop test, Fig. 5, and those induced by BIT, Fig. 12, we note that $\sigma_n$ plays a more significant role in the failure mechanism of a board-level drop test rather than that of BIT. Also noted is that these slopes are different from those obtained in our previous numerical studies [24,26] because of different constitutive relationships for the solder alloys.

4. Reliability Indices

Interfacial IMC fracturing is the primary failure mode of solder joints under drop impacts, in particular for lead-free solder joints [5-8]. From the previous analysis, $\sigma_n$ is also found to be several times greater than $\sigma_s$. We therefore assume that the mean value of the drop count to failure, $N_f$, is proportional to $\sigma_0$ while inversely proportional to the maximum $\sigma_n$ in a power-law formulation such that

$$N_f = a \left( \frac{\sigma_0}{\sigma_n} \right)^b$$

(2)

where $a$ and $b$ are universal constants independent of structures, materials, and assembly processes. We define

$$P = \frac{\sigma_0}{\sigma_n}$$

(3)

as the drop reliability index. A larger $P$ indicates a better drop reliability. Note that, ideally, $\sigma_n$ is obtained from the transient analysis for the board-level drop test while $\sigma_0$ is identified by correlating transient analysis for BIT with the measured impact force profile. In this study, however, due to the lack of BIT measurements, $\sigma_0$ is a prescribed magnitude.

Following this concept, we plot $P$ with respect to $F_{\text{max}}$, $E_r$, and $d_r$ in Figs. 13, 14, and 15, respectively. It is apparent from the figures that $F_{\text{max}}$, $E_r$, and $d_r$ are not particularly good BIT indices to correlate with the drop reliability index $P$ because the correlations are not universal; they vary according to different solder compositions.
From Figs. 13 through 15, we note that curves for solder joints of different compositions are close when $E_r$ is small. This indicates that, compared to $F_{\text{max}}$ or $d_r$, under the circumstance that $P$ is small, $E_r$ or a physical term related to the impact energy serves as a good indicator of drop reliability of board-level solder joints regardless of their compositions. This particular feature has been reported by Wong et al. [1] and Yeh et al. [14] from experimental observations. However, when $\sigma_0$ of the solder joint increases, plasticity develops around the location where fracturing initiates [25], and hence the curves vary significantly according to different solder compositions. Consequently, the correlations between $P$ and these BIT characteristics become non-universal.

To obtain universal correlations between $P$ and these BIT characteristics, here we propose to multiply $F_{\text{max}}$, $E_r$, and $d_r$ by constant multipliers, $f_a$, $f_b$, and $f_c$, respectively. Magnitudes of these multipliers are listed in Table 4 for different solder alloys. Note that these magnitudes are empirically selected without a theoretical background.

### Table 4: Multipliers for different solder alloys

<table>
<thead>
<tr>
<th>Solder alloy</th>
<th>$f_a$</th>
<th>$f_b$</th>
<th>$f_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC405</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>SAC305</td>
<td>1.10</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>SAC266</td>
<td>0.90</td>
<td>0.55</td>
<td>0.70</td>
</tr>
<tr>
<td>SAC105</td>
<td>1.10</td>
<td>0.60</td>
<td>0.60</td>
</tr>
<tr>
<td>SACXY1</td>
<td>0.90</td>
<td>0.65</td>
<td>0.80</td>
</tr>
<tr>
<td>SACXY2</td>
<td>1.10</td>
<td>1.00</td>
<td>0.85</td>
</tr>
<tr>
<td>SACXY3</td>
<td>1.10</td>
<td>1.15</td>
<td>1.00</td>
</tr>
<tr>
<td>SACXY4</td>
<td>1.15</td>
<td>1.10</td>
<td>0.95</td>
</tr>
<tr>
<td>SACSb</td>
<td>0.90</td>
<td>0.70</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Correlations between $P$ and $f_a \times F_{\text{max}}$, $f_b \times E_r$, and $f_c \times d_r$ are plotted in Figs. 16, 17, and 18, respectively. With the empirical multipliers, the modified correlations appear to be universal, i.e., independent of solder compositions. However, physical meanings of these multipliers certainly require further investigations.

5. Conclusion

Board-level drop test and package-level BIT are examined numerically in this paper. Different Sn-Ag-Cu solder joint compositions, namely, SAC405, SAC305, SAC266, and SAC105, and Sn-Ag-Cu solder alloys doped with trace elements, namely, SACSb, SACXY1, SACXY2, SACXY3, and SACXY4, are considered. Through numerical solutions, insights into the analytical correlation between the drop reliability and characteristics of the impact force profile are provided.

We note that $F_{\text{max}}$ and $d_r$ are not particularly good BIT indices to correlate with board-level drop reliability because their correlations are not universal, varying according to different compositions of the solder joints. Nevertheless, $E_r$ can be a reasonably good indicator as long as $P$ is small. Although the correlations become universal by introducing constant multipliers to these indices, physical meanings of these empirically chosen multipliers certainly require further investigations. Besides, numerical solutions presented in this paper follow rate-independent constitutive relationships for
the solder alloys. For these dynamic problems, rate-dependent constitutive relationships are in serious need.

Acknowledgment
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References