Finite Element Analysis for Monitoring Interface Crack between Solder Ball and Copper by Direct Current Potential Difference Method *

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Abstract
In order to validate the applicability of the direct current potential difference method (DC-PDM) to the identification of interface cracks, electric field analysis was carried out for a copper plate with a solder ball joined on its surface by the finite element method. The analysis was carried out for different crack depths under the following four conditions: (a) when the shape of interface crack between solder ball and copper changes, (b) when the radius of solder ball changes, (c) when the distance between the bottom of inserted copper wire and the interface changes, and (d) when the angle of inserted copper wire changes. It was found from the analysis results that a large crack area ratio gave a large increase in the potential difference and that the effect of crack shape and the angle of copper wire on the potential difference was small. Finally, the relationship between the crack area ratio and the increase in potential difference was given by a single formulated curve for all the conditions discussed in the present analysis.

Key words: Nondestructive Inspection, Crack Propagation, Finite Element Method, Direct Current Potential Difference Method, Solder Ball, Copper, Interface Crack

1. Introduction
Solder materials are widely used for electric connections in various electric products and electronics devices. Especially in the field of electronic packages, the size of solder balls and solder connections has been smaller and smaller with a recent development of electronic packages from QFP (Quad Flat Pack), BGA (Ball Grid Array), and CSP (Chip Scale Package) (1). Since the solder materials are much softer than the other materials used in the package, the deformation is likely to be concentrated on the solder when a mechanical force or a change in the temperature is given. In addition, as electronic packages can be recognized as a kind of composite structures of metals, plastics and ceramics, the evaluation of strength at the solder joint is not easy. For these reasons, the strength of solder joints has been investigated from many points of view based on the results of mechanical

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analysis using the finite element method, and those of shearing, bending, tensile, and compressive mechanical tests (2)-(8).

Sn-Pb eutectic solder has been a mainstream material for micro solder bondings. However the Sn-Pb eutectic solder was prohibited in the European Union for the toxicity of Pb July 2006 according to the Restriction of Hazardous Substances (RoHS) Directives. The reliability of lead-free solder joints has not been secured due to the lack of experimental and analytical data for strength evaluation (9), (10).

Considering above situation, the authors proposed an experimental method for evaluation of interface strength between solder ball and copper plate in which several solder balls were joined on the surface of copper plate specimen and the cyclic loading was given to the plate specimen (11). In this method, a small magnitude of direct-current is supplied to the interface between solder ball and plate specimen during the test. The growth of interface crack is monitored continuously based on the potential difference measured. This method enables us to investigate the crack growth behavior and to make a mechanical discussion on the interface crack. However, the relationship between the condition of the interface crack and the potential difference is necessary to carry out the proposed monitoring accurately. In this study, the electric field analysis was carried out for various size and shape of cracks, and various radii of solder balls using the finite element method. A universal equation which relates the condition of interface crack to the potential difference was obtained.

2. Method of Analysis

2.1 Conditions of analysis and models

Figure 1 shows the geometry of analysis model. A solder ball with a radius of 0.38 mm (different radii were used in part as will be seen) was joined at the center of a copper plate of 35 mm in length, 4 mm in width and 1 mm in thickness. A thin copper wire with a diameter of 0.1 mm was inserted from the top of solder ball. The detailed geometry of solder ball is given in Fig.2. A hatched part in the top right figure shows the shape of joining part on the interface and this figure shows a case without crack. In this study, it was assumed that electric current of 1 A was supplied at the end A, i.e., the top of copper wire, out of the end B, i.e., the left end of copper plate. The potential difference between these points was calculated by the finite element method. In this study, the following conditions which may affect the potential difference were examined in addition to the crack depth:

![Fig. 1 Whole view of analysis model of solder ball joined on the copper plate. Copper wire is inserted on the top of the solder ball.](image-url)
(a) crack shape,
(b) radius of solder ball,
(c) distance between the interface and the bottom of copper wire,
(d) insertion angle of copper wire.

Software used is one of the commercial FEM packages, the FEMLEEG Ver.3.4 produced by HoctSystem Co. Ltd. An example of the finite element mesh is shown in Fig.3. The electric conductivities of copper plate and wire (Cu) and solder ball (Sn) are shown in Table 1. In this study, a solder ball was assumed to be lead-free and its electric conductivity was given by that of pure tin.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electric conductivity [S/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>$5.977 \times 10^7$</td>
</tr>
<tr>
<td>Sn</td>
<td>$0.781 \times 10^7$</td>
</tr>
</tbody>
</table>

Fig. 2  Solder ball and copper plate without crack on the interface.

Fig. 3  Example of finite element mesh.
2.2 Effect of crack shape

Three models shown in Figs.4 to 6 were adopted to investigate the effect of crack shape on the potential difference. The first is model A where a pair of truncated circular cracks were introduced symmetrically with reference to the center of the interface, as shown in Fig.4. The depth of the cracks, \( d_1 \), was given as the largest distance between the periphery of the initial interface and the front edge of crack.

The second is model B where a pair of crescent cracks were introduced, as shown in Fig.5. The ligament part of the interface was made by adding a pair of semi-ellipses to the original ligament part of model A. Consequently, the major axis of the added semi-elliptical parts is equal to the length of the straight front edge of crack in model A. Their minor axis corresponds to the extended length of the ligament part and is denoted by \( d_2 \). In model B, \( d_1 \) was kept constant at 0.15mm and only the value of \( d_2 \) was varied.

Moreover, the third model C shown in Fig.6 was adopted, where a toroidal crack was introduced from the periphery of the initial interface. The crack depth \( d_1 \) was given by a distance from the initial circular interface to the front edge of interface crack.

The detailed conditions for models A to C are shown in Table 2. In these models, the radius of solder ball, \( r \), was kept constant at 0.38mm.
Fig. 5  Model B in which a pair of crescent cracks are on the interface between solder ball and copper plate.

Fig. 6  Model C in which a circumferential crack is on the interface between solder ball and copper plate.

Table 2  Conditions, the number of nodes and elements for models A to C.

<table>
<thead>
<tr>
<th>Model</th>
<th>Crack depth $d_1$ [mm]</th>
<th>Degree of crescent $d_2/d_1$</th>
<th>Number of nodes</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0 (no crack)</td>
<td>0</td>
<td>—</td>
<td>49584</td>
<td>85088</td>
</tr>
<tr>
<td>A1</td>
<td>0.1</td>
<td>—</td>
<td>81315</td>
<td>145632</td>
</tr>
<tr>
<td>A2</td>
<td>0.15</td>
<td>—</td>
<td>77801</td>
<td>139344</td>
</tr>
<tr>
<td>A3</td>
<td>0.2</td>
<td>—</td>
<td>75449</td>
<td>132576</td>
</tr>
<tr>
<td>B0 (=A0)</td>
<td>0</td>
<td>—</td>
<td>49584</td>
<td>85088</td>
</tr>
<tr>
<td>B1</td>
<td>0.15</td>
<td>0.05/0.15</td>
<td>80969</td>
<td>145264</td>
</tr>
<tr>
<td>B2</td>
<td>0.15</td>
<td>0.1/0.15</td>
<td>88837</td>
<td>161824</td>
</tr>
<tr>
<td>C0 (=A0)</td>
<td>0</td>
<td>—</td>
<td>49584</td>
<td>85088</td>
</tr>
<tr>
<td>C1</td>
<td>0.05</td>
<td>—</td>
<td>87865</td>
<td>160608</td>
</tr>
<tr>
<td>C2</td>
<td>0.1</td>
<td>—</td>
<td>79481</td>
<td>143392</td>
</tr>
<tr>
<td>C3</td>
<td>0.15</td>
<td>—</td>
<td>76537</td>
<td>136736</td>
</tr>
</tbody>
</table>

N.B.  Radius of solder ball $r = 0.38$ [mm]
2.3 Effect of radius of solder ball

In models D and E, the radius of solder ball was varied from that for the previous models A to C and assumed to be 0.19mm and 0.57mm, respectively, as shown in Figs. 7 and 8. In these models, the shape of crack was toroidal and its depth was given by \( d_1 \) in the same manner as for the model C. The analysis conditions in models D and E are shown in Table 3.

![Figure 7 Model D in which a circumferential crack is on the interface between smaller solder ball and copper plate.](image1)

![Figure 8 Model E in which a circumferential crack is on the interface between larger solder ball and copper plate.](image2)

**Table 3** Conditions, the number of nodes and elements for models D and E.

<table>
<thead>
<tr>
<th>Model</th>
<th>Radius of solder ball ( r ) [mm]</th>
<th>Crack depth ( d_1 ) [mm]</th>
<th>Number of nodes</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0 (no crack)</td>
<td>0.19</td>
<td>0</td>
<td>53887</td>
<td>93088</td>
</tr>
<tr>
<td>D1</td>
<td>0.19</td>
<td>0.02</td>
<td>95624</td>
<td>175840</td>
</tr>
<tr>
<td>D2</td>
<td>0.19</td>
<td>0.05</td>
<td>85576</td>
<td>154976</td>
</tr>
<tr>
<td>D3</td>
<td>0.19</td>
<td>0.07</td>
<td>85576</td>
<td>154464</td>
</tr>
<tr>
<td>E0 (no crack)</td>
<td>0.57</td>
<td>0</td>
<td>49584</td>
<td>85088</td>
</tr>
<tr>
<td>E1</td>
<td>0.57</td>
<td>0.12</td>
<td>85945</td>
<td>155296</td>
</tr>
<tr>
<td>E2</td>
<td>0.57</td>
<td>0.16</td>
<td>80057</td>
<td>144480</td>
</tr>
<tr>
<td>E3</td>
<td>0.57</td>
<td>0.24</td>
<td>78905</td>
<td>141664</td>
</tr>
</tbody>
</table>
2.4 Effect of distance between the interface and the bottom of copper wire

In order to investigate the effect of the location of copper wire on the electric potential difference, the distance between the bottom end of copper wire and the solder ball/copper plate interface, \( h \), was varied in model F, as shown in Fig. 9. In this model, the bottom end of wire was moved vertically with its length being constant. The analysis conditions for model F are shown in Table 4.

![Fig. 9 Model F in which the distance between the bottom of copper wire and the interface is changed.](image)

Table 4  Conditions, the number of nodes and elements for model F.

<table>
<thead>
<tr>
<th>Model</th>
<th>Crack depth ( d ) [mm]</th>
<th>Distance to copper wire ( h ) [mm]</th>
<th>Number of nodes</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>F01 (no crack)</td>
<td>0</td>
<td>0.114</td>
<td>48559</td>
<td>83040</td>
</tr>
<tr>
<td>F1</td>
<td>0.1</td>
<td>0.114</td>
<td>77688</td>
<td>139232</td>
</tr>
<tr>
<td>F02 (C0)</td>
<td>0</td>
<td>0.228</td>
<td>49584</td>
<td>85088</td>
</tr>
<tr>
<td>F2 (C2)</td>
<td>0.1</td>
<td>0.228</td>
<td>79481</td>
<td>143392</td>
</tr>
<tr>
<td>F03 (no crack)</td>
<td>0</td>
<td>0.342</td>
<td>48948</td>
<td>83808</td>
</tr>
<tr>
<td>F3</td>
<td>0.1</td>
<td>0.342</td>
<td>79613</td>
<td>143200</td>
</tr>
</tbody>
</table>

2.5 Effect of insertion angle of copper wire

In this study, a model which has a different insertion angle of copper wire, \( \alpha \), was adopted. The model is schematically shown in Fig. 10 and called model G. The analysis was carried out in two dimensions for model G due to the matter of software used. The detailed conditions, the number of nodes and elements are shown in Table 5.

![Fig. 10 Model G in which the insertion angle of copper wire is changed.](image)
3. Analysis Results and Discussions

3.1 Effect of crack shape

The relationship between the increase in potential difference $\Delta V$ and the crack area ratio $f$ for models A to C is shown in Fig. 11, where $\Delta V$ is the increase in electric potential difference which is calculated by subtracting the initial potential difference with no interface crack from that with an interface crack. The crack area ratio, $f$, is defined as the ratio of the area of interface crack to that of the initial interface area. As can be seen from Fig. 11, the value of $\Delta V$ increases with increasing $f$. In addition, all the results are plotted on the same curve without reference to the crack shape. This suggests that the effect of crack shape on the potential difference is small.

![Fig. 11](image)

3.2 Effect of radius of solder ball

The relationship between $\Delta V$ and $f$ for models D and E is shown in Fig. 12. The effect of the radius of solder ball is relatively large. Large solder balls in model E show smaller potential differences than those in model D at the same value of $f$.

![Fig. 12](image)
3.3 Effect of distance between interface and bottom end of copper wire

The results for model F is shown in Fig.13. Although the value of \( h \) is changed from 0.114mm to 0.342mm, \( \Delta V \) fluctuates very little. It can be concluded that the effect of the distance between the bottom end of copper wire and the solder ball/copper plate interface on the potential difference is small.

3.4 Effect of insertion angle of copper wire

The results for model G is shown in Fig.14. As described previously, the result for model G was obtained by two-dimensional analysis. Therefore, the increase in potential difference shown on the ordinate axis takes larger values than the previous results. It is found from Fig.14 that the increase in potential difference slightly changes against the insertion angle of copper wire. The effect of insertion angle on the increase in potential difference is small.
4. Relationship between Normalized Increase in Potential Difference and Crack Area Ratio

All the results for models A to E obtained by three-dimensional analyses are plotted together in Fig.15. It is found from this figure that the radius of solder ball affects the relationship between the increase in potential difference and crack area ratio. On the other hand, crack shape and the distance between the interface and the bottom end of copper wire have a very small effect on the relationship. In this study, the following discussions were made to obtain a unified expression for all the result.

\[
\frac{\Delta V \cdot r^2}{I \cdot r} = \frac{\Delta V \cdot r}{I}.
\]  

(1)
In this study, the right part in the above equation is called as the normalized increase in potential difference. The results shown in Fig.15 are replotted in Fig.16 where the ordinate is given by the normalized increase in potential difference, $\Delta V \cdot r / I$. It is found from Fig.16 that the effect of solder ball radius disappears and all the results are on a single curve.

![Figure 16](image)

Fig. 16  Relationship between normalized increase in potential difference $\Delta V \cdot r / I$ and crack area ratio $f$ for models A to E.

Now, the curve in Fig.16 is formulated. It is assumed that the relationship between the normalized increase in potential difference, $\Delta V \cdot r / I$, and crack area ratio, $f$, is given by

$$
\frac{\Delta V \cdot r}{I} = \left( \frac{1}{1 - f^n} \right)^m - 1,
$$

where $m$ and $n$ are constants. The above expression satisfies a trivial condition that $\Delta V \cdot r / I$ is zero when no crack exists ($f=0$) and the other condition that $\Delta V \cdot r / I$ goes to infinity when the interface is completely separated ($f=1$). It was found by the method of least-squares that the most appropriate values for constants $m$ and $n$ are

$$
m = 1.962, \quad (3)
n = 0.0449. \quad (4)
$$

The relationship given by

$$
\frac{\Delta V \cdot r}{I} = \left( \frac{1}{1 - f^{0.962}} \right)^{0.0449} - 1
$$

(5)

can be used for the evaluation of crack area ratio from the increase in potential difference measured. The curve shown in Fig.16 was obtained as above.

5. Conclusions

Three-dimensional electric field analysis was carried out based on a model where a solder ball was joined on the surface of copper plate and the plate was subjected to the mechanical loading with a constant direct-current supplied through the solder ball and the plate for evaluation of interface strength. The analysis was carried out for various conditions with different depth and shape of crack, different radius of solder ball, and different insertion angle of copper wire. The results obtained are summarized as follows.

(1) The increase in potential difference $\Delta V$ increased with crack area ratio $f$. The effect of
crack shape on the relationship between $\Delta V$ and $f$ was small.

(2) The relationship between crack area ratio and the increase in potential difference was affected by the radius of solder ball. When the radius of solder ball $r$ was small, the increase in potential difference $\Delta V$ was large, and vice versa.

(3) The increase in potential difference was influenced neither by the distance between the solder ball / copper plate interface and the bottom end of copper wire, $h$, nor by the insertion angle of copper wire $\alpha$.

(4) All the results obtained in the present analysis were represented by a single curve on a plot of the normalized increase in potential difference, $\Delta V \cdot r/I$, and the crack area ratio $f$, where $I$ is the magnitude of electric current supplied to the solder ball.

References


