Adhesion features of bonded interfaces interpreted by Taguchi technique

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ABSTRACT

With the increasing applications of flip-chip technology in the microelectronics industry, the adhesion strength of interfaces in the flip-chip microelectronic structures has become an important issue for manufacturing and operation. The existence of defects in the corresponding interfaces can gradually degrade the interfacial adhesion when the package is exposed to the high temperature and humidity. The effects of IC package with different solder mask thickness under different temperature and relative humidity environment conditions on the adhesion strength were studied. The control parameters are environmental temperature, relative humidity, soaking moisture time and solder mask thickness. The interfacial adhesion strength was obtained by using a dynamically material testing system (MTS 810) with a set of special testing jig. Analysis of variance (ANOVA) is the statistic method used to interpret these experimental data. Taguchi technique with ANOVA is used in this paper. The significant variables (factors) can be checked from Taguchi techniques, which indicate a very good fit to the estimated regression equation for the moisture weight gain and the interfacial adhesion strength. The research results are helpful to identify improvements required in the adhesion performance of underfill/solder mask/substrate interface.

1. Introduction

The increasing demand for high-performance and high-density plastic packages has made flip chip technology a key solution in the microelectronics industry \cite{1}. However, the reliability of flip chip assembly is also of concern during manufacturing and operation, due to the great difference in its interior material properties and characteristics.

The underfill used in flip chip assemblies, composed of epoxy and filler particles, mechanically couples the chip and substrate, as well as filling around the solder joints. This can greatly increase the solder joint fatigue life by at least an order of magnitude \cite{2-3}. The solder mask is a thin layer of polyamide material being used in the substrate as the surface layer to define wettable areas for the soldering process \cite{4}. For application in flip chip packages, the solder mask layer also serves as an adhesive between underfill and substrate, and takes a significant portion of the interconnect thickness, even though the thickness of the solder mask ranges from 20µm to 50µm only \cite{5}.

All polymer materials will absorb water to some extent and their mechanical behavior will reflect this interaction. The effect of the absorbed moisture is to decrease its complex dynamic modulus and decrease its glass transition temperature ($T_g$) \cite{6}. For the more polar polymers, such as polyamides, the effect may be appreciable. The diffusing water disrupts the hydrogen bonding between the molecular chains of the adhesive. A decreasing of the adhesive modulus may decrease the stress concentrations in the joint. Nevertheless, since the $T_g$ of the adhesive may have been appreciably lowered, the high temperature performance of the joint will obviously have been decreased.

During solder reflow, the high temperature will result in high thermal stresses in material interfaces due to mismatches in material coefficients of thermal expansion. In addition, the hygroscopic stresses induced through moisture absorbing will add to thermal stresses to degrade the interfacial adhesion severely \cite{7-8}.
Hygroscopic stresses in over-molded wire bond Plastic Ball Grid Array (PBGA) and molded flip chip PBGA after moisture conditioned at IPC Moisture Sensitivity Standard level 3 (IPC: The Institute of Interconnecting and Electronic Circuit) have been found to be higher than that of thermal stress at the peak temperature of reflow soldering [9].

The main mechanism of adhesion for most adhesive/substrate interfaces is described by adsorption theory. This theory states that materials will adhere due to the interatomic and intermolecular forces established between the surfaces of the adhesive and substrate [6]. It has been reported that the effect of moisture on the strength of adhesively bonded joints is significant due to the deterioration of the adhesive layer and the interface, the stronger interfacial bonds increased the environmental resistance of the adhesive/substrate to attack by moisture [10]. In addition, the adhesion strength for corresponding interfaces of die passivation, underfill and solder mask materials play extremely important roles in the interconnect reliability for flip chip packages [11~12]. In the case of thermosetting polymers, more are hydraulically stable in the presence of water. However, at relative high temperature, many of these polymers will be susceptible to hydrolysis and show appreciable loss of mechanical properties and increase the rate of adhesion strength loss.

Extensive studies on the effects of moisture absorption and solder reflow on the delamination and warpage of flip chip PBGA package, and the adhesion features of underfill/die passivation/die and the reliability of solder bumps have been made [13~17]. The moisture absorbing characteristics of a PBGA package are more susceptible to solder reflow damage or reduction reliability after use [18~19]. Stability of the warpage in a PBGA package subjected to hygro-thermal loading has been analytically studied by [20]. The buckling of the PBGA package, at the solder reflow peak temperature, occurs when the theoretical and experimental moisture content reaches around 0.25 - 0.30 % weight [20~21]. However, information on hygroscopic and thermo-mechanical behaviors of the underfill/substrate adhesion is still insufficient, especially as related to the thickness of solder mask.

The objectives of this current paper are to study the effects of temperature, relative humidity, thickness of the solder mask and absorption time on the moisture weight gain and adhesion strength for the button shear test specimen. ANOVA is the statistic method used to interpret these experimental data. Taguchi technique L18 OA (orthogonal arrays) with ANOVA is used in this paper. In addition, the significant variables (factors) can be checked from Taguchi technique, which indicate a very good fit to the estimated regression equation. Therefore, the independent variables in the straight-line multiple regression equation by least squares method are exactly the same as the significant factors and the non-significant factors are neglected from Taguchi technique. The research results can be helpful to identify improvements required in the adhesion performance of underfill/solder mask/substrate interface.

2. Experiment

2.1 Materials and specimens

The specimen used in this study is a button shear test joint, as illustrated in Fig. 1. It consists of three different materials, (1) the underfill composed of 60% epoxy and 40% silica filler, (2) a photosensitive type polyamide solder mask, and (3) an epoxy-coated FR-4 substrate with copper plating on both sides.

FR-4 substrates measuring 160×160 mm were first cleaned and etched, followed by coating with solder mask and curing at 150°C for 30 minutes. Then, the FR-4 substrate with solder mask was sectioned into 70×13 mm strips which were subsequently transfer molded with the underfill. Finally, specimens were cured at 165°C for 4 hours. Three different types of thickness for the solder mask layer, 18, 46 and 64µm, were chosen for comparing the effects on shear strength. The underfill button is a truncated cone with an angle of 10.85 degrees and a height of 6 mm. The top and bottom diameters of the button are 9 mm and 11.3 mm, respectively, with a nominal bonded area of 100 mm².

Fig. 1 The dimension of the button shear test specimen.
Before the experiments proceeded, the specimens were screened by an eddy current film thickness detector (LH-330, Seiko Instruments Co., Ltd.) with accuracy of 0.1µm. A maximum 3µm error of the solder mask thickness was acceptable.

2.2 Preconditioning and simulating soldering temperature cycle

After curing, the specimens were dried by baking at 125℃ for 24 hours, and the results corresponding to different solder mask thickness are shown in Fig. 2. Then, the specimens were placed in a microprocessor-controlled environmental chamber for moisture preconditioning. Six preconditioning levels, 30℃/30%RH, 30℃/60%RH, 30℃/75%RH, 60℃/30%RH, 60℃/60%RH and 60℃/75%RH, were chosen for each trial of specimen, respectively. Moisture weight gain measurements were carried out at 48, 120 and 168 hours using an electronic balance with an accuracy of 10⁻³mg. Each trial of specimen consisting of five pieces was used at each test condition. Subsequently, the specimens were retrieved from the chamber and exposed to solder reflow simulation. Then, the button shear test was performed at room temperature.

![Fig. 2 Moisture desorption of specimen after baking at 125℃ for 24 hours](image)

2.3 Button shear test

The button shear test is widely used to measure the interfacial adhesion strength between the molding compound and leadframe [22]. In this experiment, it was used to obtain the debonding load of underfill from FR-4 substrate with solder mask layer. Shear tests were carried out on a dynamic material testing system (MTS 810) with a set of special testing jig. A constant loading rate of 0.1 mm/s with a loading height of 2.75 mm was adopted. The loading height is the perpendicular distance from the bonded plane to the point on the button where the force was applied, as shown in Fig. 3.

![Fig. 3 The schematic of button shear test.](image)
3. Methods of analysis

3.1 Analysis of variance (ANOVA)

ANOVA is the statistic method used to interpret experimental data. Taguchi technique L18 three-level OA (orthogonal arrays) for ANOVA is used in this paper. In this work, there are four main factors, i.e., two-level temperature (30/60 °C), and three-level relative humidity (30/60/75 %RH), soaking time (48/120/168 Hours) and solder mask thickness (18/46/64 µm) of solder mask layer and their interactions for analysis of variance. From classical ANOVA, it is necessarily to apply totally 270 (5×2×3×3×3) experiments. But in this paper, using Taguchi techniques, only 90 (18×5) experiments for L18 OA [23-24] are needed for weight gain (%) and debonding force (N) as shown in Table 1. In the analysis, the maximum and minimum values from each five-piece trial corresponding to the same experimental condition were neglected.

The general formula [23-24] for the sum of squares the main effect of a K-level of factor A, with \( m_i \) observations corresponding to each level \( A_i \), \( i = 1, 2, \ldots, K \), respectively, is

\[
SS_A = \left[ \sum_{i=1}^{K} \left( \frac{A_i}{m_i} \right)^2 \right] - CF
\]

(1)

where the correction factor (CF), with sum total of all observations (\( \sum y_j \)) and total number of all observations (N), is calculated:

\[
CF = \frac{\left( \sum y_j \right)^2}{N}
\]

(2)

Then, the total sum of squares, \( SS_{tot} \), is defined as:

\[
SS_{tot} = \left( \sum y_j^2 \right) - CF
\]

(3)

The mean sum of squares, \( MS_A \), is defined as ratio of the sum of squares to its degrees of freedom, \( df_A \)

\[
MS_A = \frac{SS_A}{df_A}
\]

(4)

and for the residual

\[
MS_e = \frac{SS_e}{df_e}
\]

(5)

with \( SS_e \) being the residual (error) sum of squares to its degrees of freedom \( df_e \). \( MS_e \) is otherwise known as the error variance. In testing for significance of the effect of A, the following F-ratio is calculated:

\[
F_A = \frac{MS_A}{MS_e} = \frac{SS_A}{df_A \times MS_e}
\]

(6)

If the effect of the source A were negligible, the value \( F_A \) should be about 1, that is, \( SS_A \) should be about \( df_A \times MS_e \). Therefore, \( SS'_A \), the net effect of A, so called the net variation (or pure variation) of the source A, could be estimated as:

\[
SS'_A = SS_A - df_A \times MS_e
\]

(7)

The net variation for the error, \( SS'_e \), is obtained by subtracting the net variation of all the available sources from the total sum of squares \( SS_{tot} \).

It should be careful by using F ratios, which were obtained from the classical ANOVA table, to identify the significant factors when two factors have an unequal number of levels. For example, the F ratios may seem to indicate that the factor B (a three-level factor) effect is smaller than the factor A (a two-level factor) effect, but it may be not true in a plot of the data indication. This phenomenon will appear in the section of results and discussions. Care must be taken when interpreting F ratio values while multiple-level factors and two-level
factors are mixed in one experiment. The percent contribution is a much better indicator of relative effects. The percent contribution $P$ for factor $A$ to the total variation [24] is defined as

$$P = \frac{SS'_{A}}{SS_{tot}} \times 100$$

(8)

Since some portion of the sums of squares for a factor and/or interaction was subtracted out because of error, this amount must be added to the error sum of squares in order that the total sum of squares $SS_{tot}$ is unchanged. Due to the total percent contribution must add up to 100 percent; the error contribution can be calculated by subtracting all the accountable sources from 100 percent.

The significant factors are used to interpret the F ratios, which are chosen to be independent variables for multiple regression analysis. The percent contributions of factors to the total variation can be compared with the coefficients of the straight-line multiple regression equations for factor effects consistency.

### 3.2 Linear regression analysis

There are many occasions when one has an independent variable (or regressor) that one can control, and a dependent variable (or response) that one can observe at different levels of the independent variable. On the basis of some sample observations, one may wish to estimate a functional relationship between response and regressor, in the best possible way. Known as the method of least squares can be carried out to obtain a straight-line equation from experimental data. The method can be generalized to situations involving more than one independent variable, known as multiple regression analysis [24].

In the present paper, the significant variables (factors) can be checked from Taguchi techniques, which indicates a very good fit to the estimated regression equation. Therefore, the independent variables in the straight-line multiple regression equation obtained by least squares method are exactly the same as the significant factors and non-significant factors can be neglected from Taguchi technique. The straight-line multiple regression equation from all experimental data is used to compare with the regression equation based on the method for ANOVA as mentioned in section 3.1.

In order to compare the percent contributions of factors to the total variation from ANOVA with the coefficients of the straight-line multiple regression equations for factor effects consistency, all of these four factors should be not only dimensionless but also in the same range variation, i.e., from -1 to 1, so that the factors $T$, $B$, $C$ and $D$ as shown in Table 1, can be replaced by

$$T : x_1 = \frac{Temp - 45}{15}$$

$$B : x_2 = \frac{RH - 52.5}{22.5}$$

$$C : x_3 = \frac{Hr - 108}{60}$$

$$D : x_4 = \frac{Th - 41}{23}$$

(9)

where Temp, RH, Hr and Th are temperature ($^\circ$C), relative humidity (%RH), soaking time (hours) and thickness (µm) of solder mask layer, respectively. The straight-line multiple regression equation becomes

$$W = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4$$

(10)

where $a_0$ is the sample intercept, and $a_1$, $a_2$, $a_3$ and $a_4$ are the sample regression coefficients.

It is noted that the sample regression coefficients $a_1$, $a_2$, $a_3$ and $a_4$ will be used to compare the percent contributions of factors $T$, $B$, $C$ and $D$, respectively, to the total variation for factor effects consistency in next section.

### 4. Results and discussions

In this paper, the button shear test was carried out to obtain the debonding load of the underfill/solder-mask/substrate joint and an electronic balance was used to measure its moisture weight gain corresponding
to four different main factors, i.e., two-level temperature (30/60 ℃), three-level relative humidity (30/60/75 %RH), soaking time (48/120/168 Hours) and thickness (18/46/64 µm) of solder mask layer. Each trial set, which consisting of five pieces of specimen, was used at each test conditions, but the maximum and minimum values of debonding force and moisture weight gain were neglected.

The L18 OA, corresponding to temperature taking two levels but the other factors taking three levels, is shown in Table 1. The summaries of the ANOVA results for moisture weight gain and debonding force are interpreting the F ratios relative to each other as shown in Table 2 and Table 3, respectively. The largest scale moisture weight gain is due to T1B3C3D3 which is the case of temperature 30 ℃, relative humidity 75%RH, soaking time 168 hours and thickness 64 µm as shown in Fig. 4. The worst bonded strength is due to T2B3C3D1 which is the case of temperature 60 ℃, relative humidity 75%RH, soaking time 168 hours and thickness 18 µm as shown in Fig. 5. It can be seen in Table 2 that the significant factors for moisture weight gain, corresponding to at least 95% confidence, are relative humidity (P = 26.6%), soaking time (P = 44.9%) and thickness of solder mask layer (P = 8.5%), where P is the percent contribution. In Table 3, corresponding to at least 95% confidence, the significant factors for debonding force are temperature (P = 18.2%), relative humidity (P = 20.0%), soaking time (P = 27.3%) and thickness of solder mask layer (P = 20.0%).

### Table 1 L18 OA

<table>
<thead>
<tr>
<th>Trial no.</th>
<th>T</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>30</td>
<td>48</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>30</td>
<td>30</td>
<td>168</td>
<td>64</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>60</td>
<td>48</td>
<td>18</td>
</tr>
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<td>5</td>
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<td>64</td>
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<td>7</td>
<td>30</td>
<td>75</td>
<td>48</td>
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<td>30</td>
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<td>120</td>
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<td>75</td>
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<td>18</td>
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<td>30</td>
<td>48</td>
<td>64</td>
</tr>
<tr>
<td>11</td>
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<td>30</td>
<td>120</td>
<td>18</td>
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<td>12</td>
<td>60</td>
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<td>168</td>
<td>46</td>
</tr>
<tr>
<td>13</td>
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<td>18</td>
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<tr>
<td>18</td>
<td>60</td>
<td>75</td>
<td>168</td>
<td>46</td>
</tr>
</tbody>
</table>

T: temperature (℃)  B: relative humidity (%RH)  C: soaking time (hours)  D: thickness (µm)

### Table 2 Summary of ANOVA results for moisture weight gain

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>d.f.</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
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<tbody>
<tr>
<td>T</td>
<td>0.0003</td>
<td>1</td>
<td>0.0003</td>
<td>0.6</td>
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</tr>
<tr>
<td>B</td>
<td>0.0120</td>
<td>2</td>
<td>0.0060</td>
<td>12.0#</td>
<td>26.6</td>
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<tr>
<td>C</td>
<td>0.0196</td>
<td>2</td>
<td>0.0098</td>
<td>19.6#</td>
<td>44.9</td>
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<tr>
<td>D</td>
<td>0.0045</td>
<td>2</td>
<td>0.0023</td>
<td>4.6#</td>
<td>8.5</td>
</tr>
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<td>T×B</td>
<td>0.0011</td>
<td>2</td>
<td>0.0006</td>
<td>1.2</td>
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</tr>
<tr>
<td>ERROR</td>
<td>0.0039</td>
<td>8</td>
<td>0.0005</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.0414</td>
<td>17</td>
<td></td>
<td>100</td>
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</tr>
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</table>

# At least 95% confidence.

### Table 3 Summary of ANOVA results for debonding force

<table>
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<tr>
<th>Source</th>
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<th>d.f.</th>
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<th>F</th>
<th>P</th>
</tr>
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<td>10035</td>
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</tr>
<tr>
<td>B</td>
<td>11335</td>
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<td>5668</td>
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<tr>
<td>C</td>
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<td>2</td>
<td>7609</td>
<td>22.65#</td>
<td>27.3</td>
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<tr>
<td>D</td>
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<td>2</td>
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<td>16.89#</td>
<td>20.0</td>
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<td>2</td>
<td>1340</td>
<td>3.99#</td>
<td>3.8</td>
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<tr>
<td>ERROR</td>
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<td>8</td>
<td>336</td>
<td>10.7</td>
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</tr>
<tr>
<td>Total</td>
<td>53301</td>
<td>17</td>
<td></td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

# At least 95% confidence.

The sequence of percent contributions for some significant factors may be confirmed by compared them with the coefficients of the straight-line multiple regression equations as shown in Table 4 for factor effects. In Fig. 4 Moisture weight gain response from each levels of their factors

![Fig. 4 Moisture weight gain response from each levels of their factors](image)

Fig. 5 Debonding force response from each levels of their factors

![Fig. 5 Debonding force response from each levels of their factors](image)
the comparison, all of these four factors should be not only dimensionless but also in the same range variation, i.e., from -1 to 1, so that the factors can be replaced by \( x_1 \) (temperature), \( x_2 \) (relative humidity), \( x_3 \) (soaking time) and \( x_4 \) (thickness of solder mask layer) as defined in section 3.2 and their regression coefficients are, \( a_1 \), \( a_2 \), \( a_3 \) and \( a_4 \), respectively. The independent variables in the straight-line multiple regression equation are exactly the same as the significant factors and non-significant factors can be neglected from Taguchi technique.

For the moisture weight gain case, the most significant factor is soaking time with an excellent consistency in the results, as shown in Table 4, from all of ANOVA and coefficients of the straight-line regression equations. Furthermore, the combination of ANOVA results and coefficients of the straight-line regression equations shows that the sequence of percent contributions for the moisture weight gain case is soaking time, relative humidity, thickness of solder mask layer, then temperature.

For debonding force case, these four factors are all significant as shown in Table 4. The sequences of percent contributions show excellent consistency with absolute coefficient's values of the corresponding straight-line regression equations. Both moisture weight gain and debonding force cases have indicated that the same sequence exist in both percent contributions and equation's coefficients, as shown in Table 4, for these four factors. Therefore, the sequence of percent contributions for the debonding force case is soaking time, thickness of solder mask layer, relative humidity and temperature.

Table 4 Comparison coefficients of the regression equations with percent contributions \( P_i \) of the significant factors

<table>
<thead>
<tr>
<th>Source</th>
<th>( a_1 (P_1) )</th>
<th>( a_2 (P_2) )</th>
<th>( a_3 (P_3) )</th>
<th>( a_4 (P_4) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>moisture weight gain</td>
<td>0.0256 (26.6)</td>
<td>0.0401 (44.9)</td>
<td>0.0191 (8.5)</td>
<td></td>
</tr>
<tr>
<td>debonding force</td>
<td>-23.61 (18.2)</td>
<td>-30.18 (20.0)</td>
<td>-35.27 (27.3)</td>
<td>30.46 (20.0)</td>
</tr>
</tbody>
</table>

5. Conclusions

In this paper, Taguchi technique L18 OA with ANOVA is used to interpret experimental data corresponding to at least 95% confidence. The effects of thickness of solder mask (18-64 \( \mu m \)), temperature (30-60 \( ^\circ C \)), relative humidity (30-75 \%RH) and soaking time (48-168 hours) were studied relative to the moisture weight gain and the bonded strength of the underfill/solder-mask/substrate joint. Sequentially, the straight-line multiple regression equations with the significant variables inferred from Taguchi technique are obtained by using least squares method. Based on the above discussions, the following conclusions can be made.

(a) Soaking time is the most significant factor for both the moisture weight gain and bonded strength of the underfill/solder-mask/substrate joint. The sequentially significant factors for the moisture weight gain are soaking time, relative humidity and thickness of solder mask only. The sequentially significant factors for the bonded strength are soaking time, thickness of solder mask, relative humidity and temperature. The effects of relative humidity and solder mask thickness for the bonded strength are very close.

(b) The worst bonded strength is due to soaking time 168 hours/thickness of solder mask 18 \( \mu m \)/relative humidity 75 \%RH/temperature 60 \( ^\circ C \). The largest scale moisture weight gain is due to soaking time 168 hrs/relative humidity 75 \%RH/thickness of solder mask 64 \( \mu m \) under non-significant temperature corresponding to at least 95% confidence.

(c) Effects from the factor interactions are negligible by compared with effects from their individual significant factors.

(d) Percent contributions of factors from ANOVA with Taguchi technique have excellently consistent effects to the independent variables from the corresponding straight-line multiple regression equations.

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References


