Investigation of the Adhesion Strength of Underfill/Solder Mask/Substrate Joints Under Thermal Cycling

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ABSTRACT

With the increasing application of flip-chip technology in the microelectronics industry, the adhesion strength of interfaces in the flip-chip structures is becoming an important issue for manufacturing and operation. This paper presents an experimental investigation of the adhesive strength of underfill material to solder mask coated FR-4 substrate under thermal cycling. In this study, effects of the number of thermal cycles on interfacial strength were investigated by using button shear test. The relationship between interfacial strength and the thickness of solder mask was also examined. Furthermore, the morphologies of fracture surfaces of the test specimens were analyzed by scanning electron microscopy. The results of this study show that the interfacial strength of the underfill/solder mask/substrate joint was significantly reduced by thermal fatigue. Finally, the degradation behavior and possible mechanisms were then determined on the basis of these observations.

Keywords: underfill, solder mask, adhesion, thermal cycle, button shear test

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 [1]. The advantages of closer chip bump spacing and shorter physical interconnections improve design limits and electrical performance compared to conventional bond wires [2]. 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 reduces the difference in the deformation of the chip and the substrate in the in-plane direction, and it also keeps the solder joint under compression while being subjecting to the thermal stress [3]. Accordingly, the underfill can greatly increase the solder joint fatigue life by at least an order of magnitude [4]. The solder mask, is a thin layer of photo-definable polyamide material which is used in the substrate as the surface layer to define wettable areas for the soldering process [5]. 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 only 20 to 50µm [6].
Thermally-induced stresses result from the difference in the coefficient of thermal expansion (CTE) among the materials in flip-chip configurations, often resulting in loss of interfacial adhesion and solder joint fatigue. In addition to thermal stresses, contaminants, moisture, and elevated temperature are other major factors that can gradually degrade the interfacial adhesion [7]. Moreover, thermal cycling (thermal-mechanic loading) is another important load type which causes repeated relative displacements due to differential thermal expansion and contraction between materials. During normal operation this cycling can give rise to thermal fatigue at the various material interfaces, cause defect propagation, and lead to premature failure of the structures, either directly or through subsequent environmental degradation [8]. Thus, thermal cycling is usually included in long-term reliability tests for microelectronic devices.

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 which are established between the surfaces of the adhesive and substrate [9]. In addition, it has been reported that 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 [10,11].

Since with polymeric characteristics, both the underfill epoxy and solder mask layer are viscoelastic materials. In particular, the mechanical properties of underfill have been found to have a sharp change around the glass transition temperature [12,13]. It is revealed that the underfill with a higher CTE, a lower Young’s modulus and a low glass transition temperature is more susceptible to delamination failure during thermal cycling [14,15].

Extensive studies on the adhesion features of underfill/die passivation/die and the reliability of solder bumps have been made [3,10,11,16]. In addition, a few of works have begun to investigate the influence of thermal cycling on the adhesion strength of underfill/die passivation/die interfaces, and corresponding failure mechanisms [17,18]. However, information on thermo-mechanical behaviors of the underfill/solder mask/substrate adhesion is still insufficient, especially as related to thermal fatigue.

This paper studies the effects of thermal cycling on the adhesion strength of the underfill/solder mask/substrate interface by using the button shear test. Two solder mask thicknesses were evaluated in this study. In order to investigate the fracture mechanism, the tested specimens were also observed by scanning electron microscope (SEM). 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) a epoxy-coated FR-4 substrate with copper plating on both sides. The corresponding material properties are presented in Table 1.

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. Two different thicknesses of the solder mask layers, 25µm and 50µm, were chosen for comparing the effect 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.
Table 1. Material properties of the specimen.

<table>
<thead>
<tr>
<th>material</th>
<th>E (Mpa)</th>
<th>υ</th>
<th>CTE (10^-6/℃)</th>
<th>T_g (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>underfill</td>
<td>6,300</td>
<td>0.33</td>
<td>55 &lt; T_g</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>103 &gt; T_g</td>
<td></td>
</tr>
<tr>
<td>solder mask</td>
<td>4,100</td>
<td>0.35</td>
<td>30 &lt; T_g</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70 &gt; T_g</td>
<td></td>
</tr>
<tr>
<td>copper</td>
<td>130,000</td>
<td>0.35</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>FR-4</td>
<td>E_x=E_y=17,000</td>
<td>0.42</td>
<td>α_x=α_y=18</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>E_z=7,450</td>
<td>0.13</td>
<td>α_z=58</td>
<td>---</td>
</tr>
</tbody>
</table>

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. For convenience, in the following, the test specimens with 25µm-thickness and 50µm-thickness solder mask layers are referred as TV25 and TV50, respectively.

2.2 Thermal cycling program

After curing, the specimens were placed in a microprocessor-controlled environmental chamber under the thermal cycling testing conditions specified by JESD22-A104-A. The temperature of thermal cycling ranged from 125 to -55 with a ramp rate of 36 °C/min and a dwell time of 25 minutes at peak temperatures. A typical temperature profile of a single testing cycle is shown in Fig. 2. When each additional 50 cycles were finished, five specimens of TV25 and TV50, separately, were retrieved from the chamber and then the button shear test was performed at room temperature.

2.3 Button shear test

Fig. 1. The dimension of the button shear specimen.

Fig. 2. The temperature profile of a testing cycle.
The button shear test is widely used to measure the interfacial adhesion strength between the molding compound and leadframe [19]. 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 0.1mm/s with a loading height of 2.75 mm was adopted. The x-axis is on the centerline of solder mask/substrate interface and in the opposite direction of applied load. 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)

2.4 SEM analysis

To characterize the physical features of adhesion and the effect of thermal cyclic loading on the fracture behavior of the tested specimens, a JEOL JSM-6400 scanning electron microscope, was used to observe both sides of the selected fractured specimens. The surface morphologies were then analyzed. Since the underfill and solder mask are non-conductive materials, the fractured surfaces were coated with a thin layer of carbon to eliminate charging effects.

3. Results and discussions

3.1 Effect of thermal cycling on interfacial adhesion

All experimental results showed that the failure always occurred at the interface of the solder mask and substrate. This probably results from the solder mask which is difficult to wet the natural oxides of the copper and therefore, a weaker boundary layer is formed at the solder mask/substrate interface.

Since there was no significant amount of solder mask found remaining on the substrate surface after debonding, the magnitude of debonding force can be considered as relating only to the strength of the solder mask/substrate interface. The debonding forces for both types of test specimens are plotted as a function of number of thermal cycles in Fig. 4. This shows that the adhesion strength decreases with the increase of number of thermal cycles. Apparently, the debonding force for the test specimen with larger solder mask thickness was higher than that of smaller one, and this difference in adhesion strength retention between TV25 and TV50 is related to stress distributions and energy adsorptions. Due to the differential expansion between the underfill and substrate, a thinner layer of solder mask will also result in higher shear stress, in the solder mask and along the bonded surfaces after curing. Furthermore, as the thickness of the solder mask layer is increased in the button shear test, a larger volume of solder mask is subjected to deformation per unit area of detachment so that the total energy expended in peeling increases. Therefore, increasing the thickness of adhesive layer will decrease stress concentrations in the adhesive layer and result in higher adhesion strength.
The rates of decrease for average adhesion forces with respect to number of thermal cycles for both types of specimens, TV25 and TV50, are illustrated in Fig. 5, where the rate of decrease for average adhesion force represents the percentage of loss in average joint debonding force after thermal cycling test. As can be seen, the rates of decrease for average adhesion forces for TV25 were 5.8%, 10%, 14.7%, 25.8% and 36.3%, after 100, 200, 300, 400 and 500 cycles of thermal cycling test, respectively. With regard to TV50, however, the rates were 2.0%, 6.4%, 11.9%, 26.1% and 46.4%.

Since the solder mask material is viscoelastic and exhibits mechanical hysteresis, when the test specimen is under thermal cyclic loading, some of the inelastic deformation energy will be dissipated as heat in each cycle. Thus, the thermal fatigue may occur due to excessive plastic deformation.

In addition, crack initiation and extension in adhesives, whether along the interface or in the adhesive layer, obviously involves the rupture of intrinsic bonds. Van der Walls and hydrogen bonds are considered as the main bonds for the solder.

Fig. 4. The average debonding forces as a function of number of thermal cycles.

Fig. 5. The rates of decrease for debonding forces for TV25 and TV50.
mask/substrate interface. A significant degradation of the adhesion strength of button shear test specimens under the thermal cyclic loading and long exposure at higher temperature results from the decrease of interfacial bond force.

If there are any voids or defects appear at the solder mask/substrate interface near the corners, the alternation of tensile and compressive forces relating to the thermal cycling will gradually increase the plastic strain in the vicinity of the void/defect tip. In the shear test, fracture also involves the localized viscoelastic and plastic energy dissipating at the adhesion edge. Such micromechanisms usually represent the main source of energy absorption in the material. Thus, it is noted that a higher adhesion strength is obtained from adhesive materials which have larger deformation energies within the stress limit set by the interfacial strength. Based on this contention, as the interfacial bond force decreases, the adhesion strength of the interface will also tend to reduce, especially for the thicker layers of solder mask.

In addition, the glass transition temperature $T_g$ for solder mask material adopted in this experiment is around 150 $^\circ$C. Above the $T_g$, the thermal and mechanical properties of the solder mask will change dramatically. Since the glass transition typically occurs over a temperature range of 100 $^\circ$C, the CTE and modulus of elasticity of the solder mask might change repeatedly to a significant extent during thermal cyclic loading, even although the peak temperature remains lower than the $T_g$.

In sum, the adhesion strength of the solder mask/substrate interface decreases with an increase in the number of thermal cycles, and the decrease rate for the average adhesion forces for TV50 is higher than that for TV25 after subjecting over 400 temperature cycles can be confirmed.

3.2 Fracture surface analysis

The distinct fracture types for adhesive joints are brittle and ductile fractures, although in many cases both may be involved. Figure 6 shows the relationship of debonding force versus displacement for TV50. As can be seen, the specimens tend to fail in brittle manner, and the curve for the specimen before thermal cycling test is more linear than that after testing. Furthermore, the maximum displacement during button shear test for TV50 was higher than that for TV25, e.g., 0.012mm to 0.007mm. While the specimen was under thermal cyclic loading, the amount of adhesive free volume increased as temperature increased, and thus the segmental mobility of molecular increased and the degree of internal friction and viscosity decreased. On the contrary, both the degree of internal friction and viscosity increased as temperature decreased. Therefore, this results in the increase of the loss factor of the adhesive. SEM micrographs also indicate this result; and typical scanning electron micrographs for the fractured surface of TV50 after subjecting 500 temperature cycles are presented in Fig. 7. Here, the solder mask surface of the specimen shows furrows and greater plastic deformation in the direction of applied shear force. In addition, traces of the adhesive, shown in Figs. 8(a) and 8(b), were observed on the fractured substrate surfaces, distributed more uniformly before thermal cycling test than afterwards. This indicates that the bonding strength was degraded throughout the dynamic thermal fatigue test.

![Fig. 6. The load-displacement curve for button shear test.](image-url)
4. Conclusions

The effects of solder mask thickness and number of thermal cycles are studied relative to the bond strength of the underfill/solder mask/substrate joint. Based on the above discussions, the following conclusions can be made.

(1) The debond force for test specimens with 50µm solder mask thickness was higher than that for 25µm solder mask thickness. The difference in adhesion strength retention between test specimens with 25µm and 50µm solder mask thicknesses was related to stress distribution and energy adsorption.

(2) The adhesion strength decreased with the increase of number of thermal cycles. Corresponding factors for the loss of bond strength includes the chemical degradation of the adhesive and the inelastic deformation energy dissipation, etc. Under thermal cycling, test specimens with 25µm solder mask thickness, the decrease rate for the adhesion forces was higher than that for the 50µm solder mask thickness before 350 temperature cycles. However, it is in reverse order after 400 temperature cycles.

(3) From SEM analyses, it was found that the solder mask surface of the specimens subjected to thermal cycling showed furrows and more plastic deformation in the direction of applied shear force than the specimens not subjected to thermal load.

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References


