

Interfacial Delamination Mechanisms During Soldering Reflow With Moisture Preconditioning

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Abstract—This paper first examines the commonly-used thermal-moisture analogy approach in moisture diffusion analysis. We conclude that such an analogy using a normalized concentration approach does not exist in the case of soldering reflow, when the solubility of each diffusing material varies with temperature or the saturated moisture concentration is not a constant over an entire range of reflow temperatures. The whole field vapor pressure distribution of a flip chip BGA package at reflow is obtained based on a multiscale vapor pressure model. Results reveal that moisture diffusion and vapor pressure have different distributions and are not proportional. The vapor pressure in the package saturates much faster than the moisture diffusion during reflow. This implies that the vapor pressure reaches the saturated pressure level in an early stage of moisture absorption, even the package is far from moisture saturated. However, the interfacial adhesion degrades continuously with moisture absorption. Therefore, the package moisture sensitivity performance will largely rely on the adhesion strength at elevated temperature with moisture. A specially designed experiment with a selection of six different underfills for flip chip packages was conducted. Results confirm that there is no correlation between moisture absorption and the subsequent interface delamination at reflow. The adhesion at high temperature with moisture is the only key modulator that correlates well with test data. Such a parameter is a comprehensive indicator, which includes the effects of thermal mismatch, vapor pressure, temperature and moisture. In this paper, a micromechanics based mechanism analysis on interfacial delamination is also presented. With the implementation of interface properties into the model study, it shows that the critical stress, which results in the unstable void growth and delamination at interface, is significantly reduced when the effect of moisture on debonding is considered.

Index Terms—Interface delamination, moisture diffusion, moisture sensitivity, underfill, vapor pressure.

I. INTRODUCTION

THE problem of moisture absorption and subsequent package failure at elevated temperature is very important to the reliability and integrity of microelectronic devices [1]–[3]. Despite the diversities in chemistry and compositions,

most of polymeric materials in electronic packages are susceptible to moisture absorption. Moisture condenses in numerous micro- or nano- pores, free-volumes, interfaces, and micro- or macro- voids in diffusing materials. When the encapsulated microcircuits are exposed to high temperatures during infra-red reflow soldering, the temperature is rapidly raised to about 220 °C for SnPb soldering and 260 °C for lead-free soldering, respectively. The moisture vaporizes and the simultaneous action of thermal stresses and internal vapor pressure drives interfacial delamination and package blister. A ‘popping’ sound may be detected if water vapor is suddenly released due to the crack propagation to the surface of packages. Such kind of failures, so-called “popcorn failure,” was first reported in 1985 by Fukuzawa *et al.*[4].

Moisture is absorbed into polymeric materials in two ways. The first is as free or “unbound” water liquid or vapor, which collects at micro- or nano- pores, free volumes, interfaces, and micro- or macro voids. More than 90% of the absorbed moisture stays in bound water state [5]. Moisture can also be absorbed by water-polymer affinity for each other due to the availability of hydrogen bonding sites along the polymer chains and interfaces, which are known as “bound water.” The formation of hydrogen bond with polymer materials causes the hygroscopic swelling of material, while the unbound water liquid/vapor fills in free volumes, which does not cause swelling if the vapor pressure is low at lower temperatures. For most of polymer materials, moisture absorption is a reversible process and there is no chemical reaction involved [6].

Like other mass diffusion, moisture diffusion behavior is often described by the Fick’s law [7]. Therefore, the moisture diffusion analysis is analogous to heat transfer analysis. However, moisture concentration is usually discontinuous along bimaterial interface due to the difference in solubility for each material. The basic solution variable in mass diffusion is therefore defined as the ‘normalized concentration’, $\phi = C/S$, where C is the moisture concentration of the diffusing material and S is its solubility [8]. The normalized concentration is continuous across the interface between the different materials. Galloway *et al.*[9] and Tay and Lin [10], [11] applied such a normalized approach to obtain the local moisture concentration at the location of the interest. Wong *et al.* [12] introduced an alternative normalized solution variable, so-called wetness, to solve the same problems.

Moisture diffusion is a process of the condensation of ambient water vapor into a mixed water liquid/vapor state in diffusing material. For instance, the saturated moisture concentration at 85 °C/85%RH for a typical underfill is $1.25 \cdot 10^{-2} \text{ g/cm}^3$

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[1], [13]. The ambient water vapor density at 85 °C/85%RH is $0.85 \cdot \rho_g = 3.04 \cdot 10^{-4} \text{g/cm}^3$, where ρ_g is the ambient saturated moisture density (obtained from the steam table). A simple calculation of the ratio between the saturated moisture concentration and the ambient water vapor density, which is 80.2, reveals that the moisture must be condensed into liquid phase within the material. Polymer materials behave like a sponge in absorbing moisture. The liquid water in the material will vaporize when the temperature rises. However, the moisture in material at elevated temperature may not be fully vaporized if there is sufficient amount of moisture existing. This means that the moisture may still be in a mixed liquid/vapor phase at elevated temperature.

Vapor pressure exists anywhere in diffusing material. Vapor pressure will increase exponentially when temperature rises. Since moisture stays in micro- or nano- pores of material, a multiscale analysis is necessary to link the moisture diffusion to the phase change of moisture in micro- or nano-pores and to the evolution of vapor pressure. Fan *et al.* [14]–[16] has developed a multiscale micromechanics based vapor pressure model to estimate the vapor pressure evolution at reflow.

Many investigations have attempted to identify the critical material properties on moisture sensitivity performance during reflow. Kitano *et al.* [17], Tay and Lin [10], [18] conducted a series of work on the moisture diffusion and heat transfer in plastic integrated circuit (IC) packages, and studied the dynamics of moisture diffusion, hygrothermal stresses and delamination using an interface fracture mechanics approach. They concluded that the local moisture concentration, not the total moisture weight gain has direct correlation to the moisture performance. Fauty *et al.* [19] correlated adhesion/delamination to various mold compound properties in an attempt to determine which properties from a users standpoint are important in the selection of a proper mold compound to withstand the stresses induced by moisture loading and subsequent reflow at 260 °C. Luo and Wong [20] investigated the influence of temperature and humidity on the adhesion performance of underfill material by die shear test after exposure to various conditions. It is apparent from vast references that it would be difficult to formulate a hypothesis based on the mechanical/material properties of a polymeric material owing to the mixed effects and sometimes contrasictory information given. However, the one property that does seem to stand out for consistency is adhesion. It is logical to assume that more tenacious the adhesion the harder it is for delamination and subsequent cracking to occur.

This paper will start from a reexamination of thermal-moisture analogue approach in moisture diffusion. The limitation of the normalized concentration approach in desorption modeling at reflow is discussed. The multiscale vapor pressure model is applied to obtain a whole-field vapor pressure distribution for a flip chip package. Moisture absorption, adhesion characteristics, thermal and mechanical properties of various types of underfills are investigated to determine whether these properties could be correlated to the moisture sensitivity performance. A controlled design of experiment was conducted to verify the hypothesis proposed based on vapor pressure and moisture diffusion

analysis. The last section of the paper presents a framework of a micromechanics based mechanism analysis for void behavior at different stages at interfaces.

II. MOISTURE DIFFUSION

Moisture concentration is discontinuous across the material interface, when the two materials which have the different saturated concentration C_{sat} are jointed [11]. The interfacial discontinuity can be removed by normalizing the field variable, such as

$$\varphi = C/S \quad (1)$$

where C is the moisture concentration and S is the solubility. The solubility S is the material property and the function of temperature.

This normalization approach is efficient to perform the moisture diffusion analysis during soaking at constant ambient temperature and humidity conditions, since the governing differential equation is analogous to the heat transfer, as follows:

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = \frac{1}{D} \frac{\partial \varphi}{\partial t} \quad (2)$$

and the interfacial continuity

$$C^{(1)} / S_1 = C^{(2)} / S_2 \quad (3)$$

where x, y, z are coordinates, D is the moisture diffusivity, t is the time, $C^{(1)}$ is the moisture concentration at the interface on the material 1 (Mat1) side, $C^{(2)}$ is the moisture concentration at the interface on the material 2 (Mat2) side, S_1 and S_2 are the solubility of the Mat1 and Mat2, respectively.

Let us look at a general case when the solubility S is a function of temperature T , which is dependent on the time t . The governing differential equation becomes

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} + \frac{\partial^2 \varphi}{\partial z^2} = \frac{1}{D} \frac{\partial \varphi}{\partial t} + \frac{\varphi}{D \cdot S} \frac{\partial S}{\partial t} \quad (4)$$

in which

$$\frac{\varphi}{D \cdot S} \frac{\partial S}{\partial t} \neq 0. \quad (5)$$

This implies that the thermal-moisture analogy based on the normalization approach is not valid when the term in (5) is not equal to zero. When a package undergoes soldering reflow after moisture preconditioning, the ambient temperature changes with time. Therefore, the previously developed normalized concentration approach can not be applied to solve the desorption of moisture correctly. The normalized concentration with respect to the saturated moisture concentration (so-called wetness) is continuous only when the saturated moisture concentration is constant in an entire temperature range of reflow for all polymer materials. Otherwise, special treatment must be introduced to perform the moisture diffusion properly [21].

III. WHOLE FIELD VAPOR PRESSURE DISTRIBUTION IN FLIP CHIP PACKAGES

The vapor pressure in the materials or along the interface is the results of the expansion of water from liquid phase to steam

during reflow cycle. Most of vapor pressure models in literature predict the vapor pressure in delaminated interfaces, and are not suitable for investigating the vapor pressure buildup in materials during reflow. Because moisture exists everywhere in polymer materials in an electronic package after moisture preconditioning, the understanding of whole field vapor pressure distribution is necessary. In order to describe the condensation of moisture into a mixed liquid/vapor phase in micro pores, a microscopic level analysis is needed. In the microscopic level, the attention is focused on a representative elementary volume (REV) around any considered point. The REV is defined in such a way that wherever it is placed within the considered domain, it always contains both the solid phase and the porous phase, and the moisture content in this representative volume is obtained as the moisture concentration from the moisture diffusion analysis at a macroscopic level. Furthermore, both the solid phase and the porous phase are assumed to be more or less evenly distributed within the REV. Therefore, the interstitial space fraction f (or free volume fraction), which is considered as the intrinsic material property, can be introduced. Fan *et al.* [14]–[16] developed a micromechanics-based vapor pressure model, in which three distinct cases are identified to describe the moisture states in the pores. The first case is when the moisture density in the voids is low enough such that all the moisture becomes vaporized at preconditioning temperature T_0 , i.e., $T_c \leq T_0$. In the second case, the moisture is not fully vaporized even at reflow temperature T_r , i.e., $T_c \geq T_r$. In the last case, the moisture is fully vaporized at a temperature between preconditioning T_0 and the peak reflow temperature T_r , i.e., $T_0 \leq T_c \leq T_r$. For each case, the vapor pressure can be written as follows:

Case 1: when $C_0/f_0 \leq \rho_g(T_0)$

$$p(T) = \frac{C_0 p_g(T_0)}{\rho_g(T_0) f} \frac{T}{T_0} [1 - 3\alpha(T - T_0)]. \quad (6)$$

Case 2: when $(C_0)/(f)[1 - 3\alpha(T - T_0)] \geq \rho_g(T)$

$$p(T) = p_g(T). \quad (7)$$

Case 3: when $C_0/f_0 > \rho_g(T_0)$, and $(C_0)/(f)[1 - 3\alpha(T - T_0)] < \rho_g(T)$

$$p(T) = p_g(T_1) \frac{T}{T_1} \frac{f(T_1)}{f} \frac{1 - 3\alpha(T - T_0)}{1 - 3\alpha(T_1 - T_0)}. \quad (8)$$

From the above equations, it can be seen that the vapor pressure depends on the local moisture concentration, and the current void volume fraction. Three scenarios of vapor pressure buildup during reflow are described by those equations. The Case 1 will not likely happen in most circumstances, which will be illustrated in the whole-field vapor pressure distribution. The Case 2 implies that the moisture in materials is still in liquid/vapor phase at the peak reflow temperature, thus the saturated vapor pressure, which increases exponentially with temperature, is remained. The Case 3 corresponds to the case where the transition from liquid state to vapor state take places during reflow before the peak temperature is reached. In this case, the vapor pressure is not as high as the saturated vapor pressure.

A 2-D finite element model is generated for a flip chip BGA package in both molded and unmolded format. In this model,

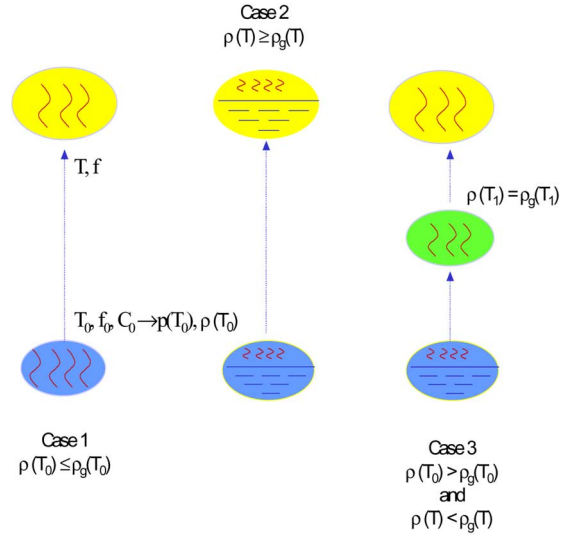


Fig. 1. Three distinct cases for the vapor pressure evolution from the preconditioning temperature T_0 to the current reflow temperature T .

die, copper pad, and solder bump do not absorb moisture, and are assigned with very small values of diffusivity and solubility in analysis. The vapor pressure can then be calculated by the equations shown above and the whole field contour of vapor pressure can be plotted by using a user-defined script in ANSYS. In Fig. 2, the moisture distribution and the corresponding vapor pressure contours for unmolded flip chip BGA are plotted at the time 5, 10, and 168 h, respectively. The moisture soaking condition is 85 °C/85%RH. It is found that moisture diffusion and vapor pressure have different distributions. Vapor pressure in the package saturates much faster than the moisture diffusion. This implies that even in the early stage of moisture absorption (e.g., 10 h) a saturated vapor pressure at the interface embedded in the package will be reached. The additional moisture uptake does not increase the level of vapor pressure, e.g., at underfill/chip interface. Similarly, the vapor pressure distributions at 220 °C for a molded flip chip BGA under 30 °C/60%RH condition are plotted in Fig. 3, which also show that vapor pressure at underfill/chip interface reaches the saturated vapor pressure when the package is far from the saturated moisture diffusion state (see Fig. 1).

Moisture affects the package reliability at reflow in two aspects: the generation of vapor pressure and the degradation of interfacial adhesion. Fig. 4 is a schematic plot showing the relative effect of moisture absorption on the interfacial adhesion and vapor pressure in the package. With more moisture absorbed, the vapor pressure will remain the saturated vapor pressure level. However, the interfacial adhesion continues to decrease with moisture. When the adhesion strength decreases to the level below the vapor pressure, as shown in Fig. 4, the delamination will occur.

For same material (e.g., underfill) under different soaking conditions, the more the moisture is absorbed, the more the interfacial adhesion is reduced. There is a simple correlation between the moisture absorption and adhesion. However, for different materials under same preconditioning, the rate and capacity of moisture absorption for each material, such as the

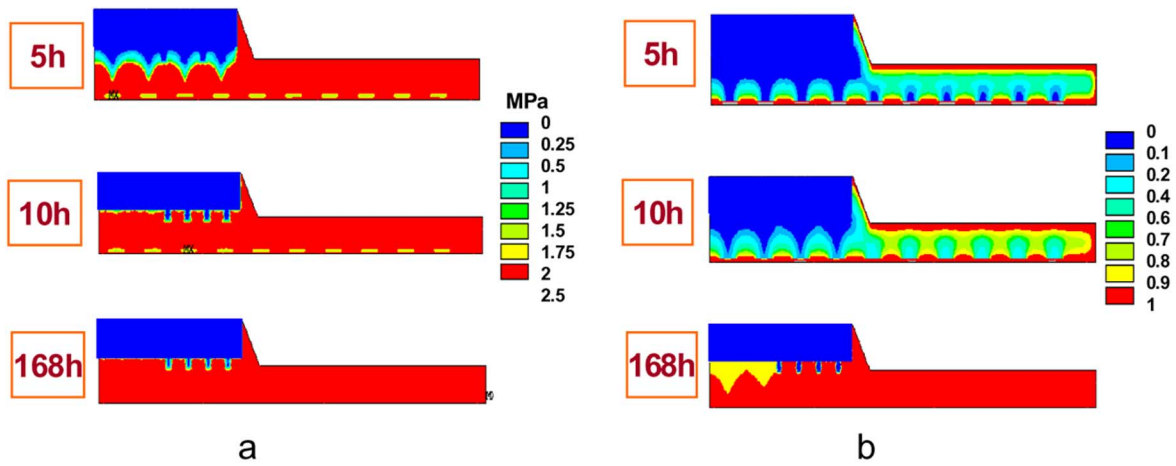


Fig. 2. Flip Chip package (not molded) at MSL level 1 at 220 °C: (a) transient vapor pressure distribution and (b) transient moisture distribution.

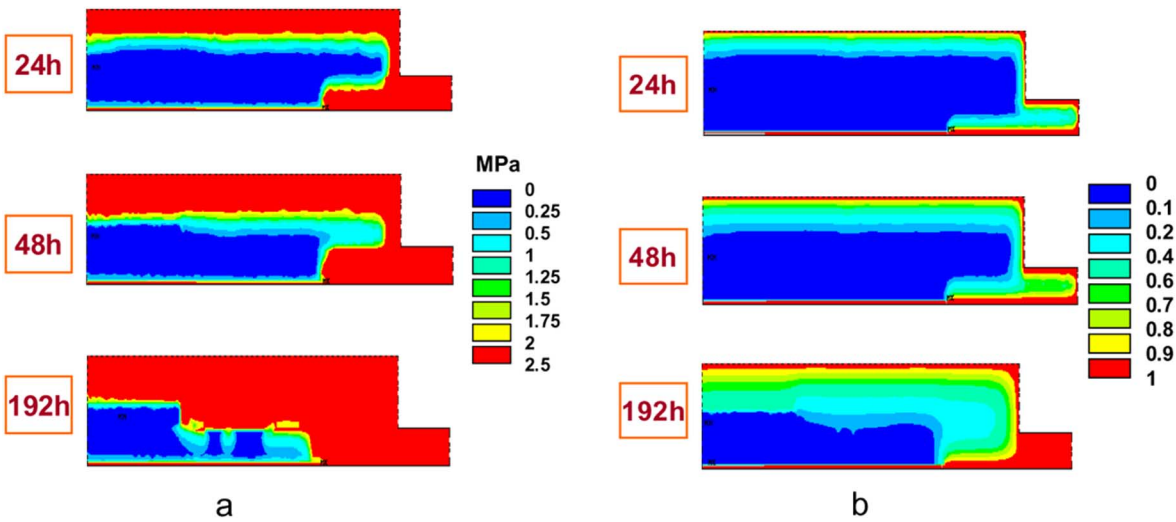


Fig. 3. Flip Chip package (molded) at MSL level 3, 220 °C: (a) transient vapor pressure distribution and (b) transient moisture distribution.

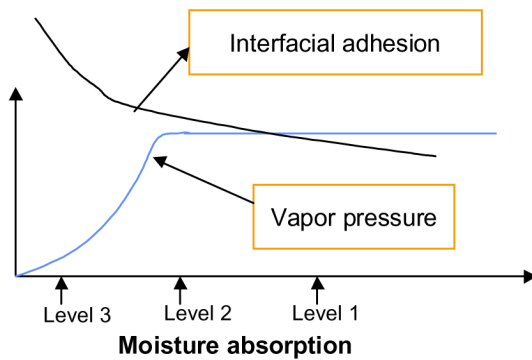


Fig. 4. Schematic of relative effect of moisture absorption on interfacial adhesion and vapor pressure.

diffusivity and saturated moisture concentration, are different. The correlation between moisture absorption and adhesion does not exist due to different chemistries and surface treatment. Although the vapor pressure is same for most cases since saturated vapor pressure can be reached in a much early stage of moisture absorption, the sensitivity of the adhesion to moisture may be

very different for different materials. This implies that it is important to select the materials, of which the adhesion is robust regardless of moisture absorption.

IV. EXPERIMENT

To examine the effect of material selection on package moisture sensitivity performance, several key material modulation factors are characterized first. Six different underfills, which have a wide range of chemistries and compositions, are selected for the evaluation. Fig. 5 shows the moisture weight gain curves of these underfills under 85 °C/85%RH preconditioning. The saturated moisture weight gain ranges from 0.5% through 1.6% of the total weight respectively. Underfill A has the least moisture absorption among six materials. Table I lists the thermal and mechanical properties of these underfills such as the CTE 1, CTE 2, Tg and E1 and E2, respectively. Since the delamination at the interface between underfill and polyimide in a flip chip package is a common failure mode in moisture sensitivity test, the adhesion measurement at room temperature using die shear setup was conducted. Fig. 6 plots the adhesion results under various soaking hours, which show that the differences in adhesion

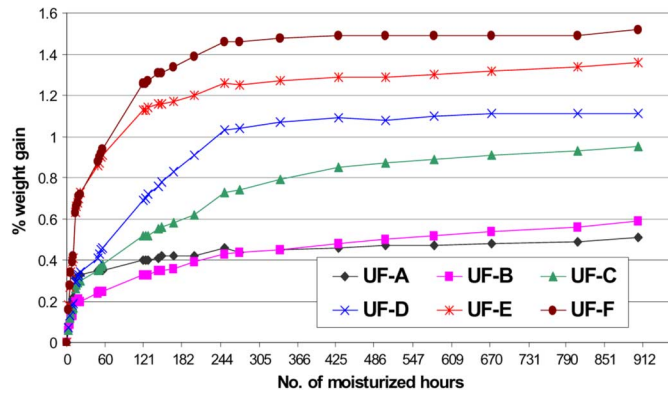


Fig. 5. Moisture weight gain data for six underfills under 85 °C/85%RH.

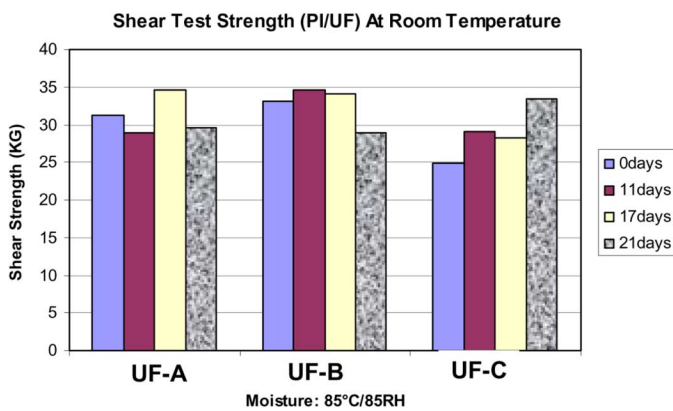


Fig. 6. Adhesion test results at room temperature with and without moisture (85 °C/85RH).

TABLE I
THERMAL AND MECHANICAL MATERIAL PROPERTIES OF SIX UNDERFILLS

UF	CTE1	CTE2	Tg	E1, E2	
	ppm/°C	ppm/°C	°C	GPa	
UF-A	31	90	133	8	1.7
UF-B	18	40	128	12	4
UF-C	25	93	117	9.6	1.4
UF-D	27	78	144	7	4.5
UF-E	68	197	155	2.2	1.05
UF-F	61	199	102	2.7	0.05

among the first three underfills at room temperature are not significant. It is also noted that the adhesions for these three underfills are not sensitive to moisture. It seems that the underfill *A* is an ideal candidate for the best moisture sensitivity performance due to its low moisture absorption and normal adhesion ability.

Four different configurations of flip chip BGA test vehicles using underfill *A* were built and tested under JEDEC moisture sensitivity level (MSL) 3. These four configurations include two different ball layouts with and without molding, respectively. Table II summarizes the test results. Unfortunately, all legs with underfill *A* failed at MSL 3 with the delamination at the interface between the underfill and the polyimide.

TABLE II
SUMMARY OF JEDEC MSL 3 TEST WITH UNDERFILL A

Leg ID	Configuration	# unit with this failure mode
A1	ball layout 1, molded	3/24
A2	ball layout 1, not molded	5/24
A3	ball layout 2, molded	4/24
A4	ball layout 2, not molded	6/24

TABLE III
SUMMARY OF JEDEC MSL 3& 2 TEST RESULTS WITH UNDERFILLS C AND E

Underfill	Total number of failure units	
	MSL 3	MSL 2
UF-C	0/24	0/18
UF-E	0/18	Not Available

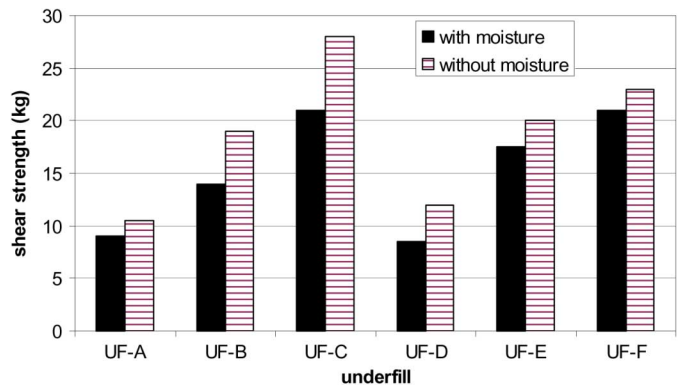


Fig. 7. Adhesion test results at 220 °C at underfill/PI.

Additional experimental legs are then built using underfill *C* and *E*, which have much higher saturated moisture concentration than underfill *A*. The test results in Table III show that the packages with underfill *C* and *E* passed JEDEC MSL 3, and the packages with underfill *C* even passed MSL 2 without any delamination.

The above results clearly demonstrate that the moisture diffusivity and saturated moisture concentration do not correlate with the moisture performance when comparing different materials' behaviors. Although underfills *C* and *E* absorb more moisture than underfill *A*, the vapor pressure buildup for all these three underfills is same during reflow according to the previous analysis. The performance difference observed in this experiment is then attributed to the difference in adhesion strength. The results shown in Fig. 6 are the adhesion strength at room temperature, which do not represent the adhesion strengths at elevated temperature. Fig. 7 plots the adhesion results at high temperature, in which dry and preconditioned samples are tested. It clearly shows that the underfill *C* has the strongest adhesion in the presence of moisture at high temperature, while underfill *A* has poor adhesion at high temperature.

The experimental results shown above indicate that the moisture absorption is not critical parameter in selecting materials for

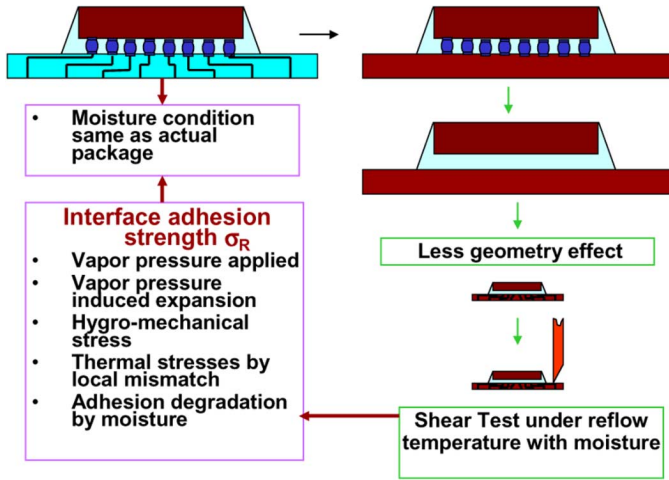


Fig. 8. Adhesion test coupon configuration.

moisture sensitivity performance. The most important parameter is the adhesion in the presence of moisture at high temperature. As a matter of fact, when the adhesion test is performed at high temperature with moisture, e.g., shown in Fig. 8, the measured value is a comprehensive parameter which includes the effects of moisture and temperature, thermal stress and vapor pressure. It concludes that when selecting material for moisture performance during reflow, moisture absorption related material properties such as diffusivity and saturated moisture concentration are not critical parameters. For a particular material, even though material is able to absorb more moisture than other materials, the delamination may not be a concern if the adhesion at the interface of interest after moisture absorption at high temperature is strong enough. The adhesion at room temperature may not be able to represent the interface behavior. Only the adhesion measurement at elevated temperature with moisture effect correlates with the reflow performance.

V. CHARACTERIZATION OF INTERFACE ADHESION STRENGTH—STUDY OF VOID BEHAVIOR AT INTERFACE

It has been very difficult to accurately define and characterize the ‘adhesion strength’ at elevated temperature. The material at high temperature becomes very compliant and the structure undergoes large deformation. Due to the small feature of adhesive layer thickness, traditionally established interface fracture mechanics approach may not be applicable. The interfacial delamination induced by moisture at reflow temperature has long been considered as the consequences of the void initiation, growth and coalescence. Therefore, it is necessary to introduce a micromechanics based approach to investigate the problem.

The void behavior at the interface is different from that within the bulk. The void growth at the interface is not only controlled by the total stress but also the interface bonding. Fig. 9 sketches the void behavior at the interface, in which three stages are involved. At the beginning, the void at the interface has an initial void volume fraction f_0 , in which a certain amount of moisture is condensed into liquid. With the increase of temperature, thermal stress and vapor pressure are developed. The void will reach the equilibrium at the grown void volume fraction f_1

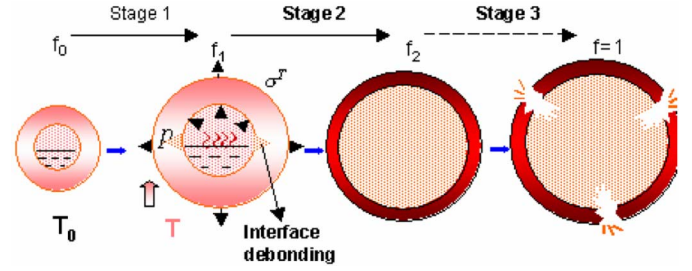


Fig. 9. Schematic description of the void behaviors at interface. Three stages are involved. Stage 1 describes the deformation during the temperature rise due to the vapor and thermal stresses. Stage 2 is the void-growth stage due to the debonding of the interface under certain stresses with the effects of the moisture intake at certain temperature. Stage 3 describes the unstable void-growth.

(Stage 1). due to the fact that the interfacial strength is weakened by the moisture uptake at high temperature, the void will continue to grow, as shown in stage 2 of Fig. 9. The new equilibrium will be reached at a new void volume fraction f_2 . At this new equilibrium position, the problem can be treated as the equilibrium for a void with the initial volume void fraction $(f_0 + f_2 - f_1)$. If the applied stress reaches the critical stress with $(f_0 + f_2 - f_1)$, the void growth becomes unstable (third stage). Otherwise, the void growth will stop here and no further delamination is formed.

The void behavior at stage 2 is related to the interface properties. A general relationship between the void-growth and the moisture contents and the temperature may be postulated as

$$\dot{f} = kCe^{-\frac{Q}{RT}} \dot{T} \quad (9)$$

where C is the moisture concentration and T the temperature, R is the universal gas constant. k and Q are interface constants to be determined. It can be seen that the rate of void-growth is proportional to moisture concentration C and temperature T . Some materials exhibit excellent resistance to moisture absorption with low C , while other materials show interface strengths being sensitive to moisture absorption with high k . There is no direct correlation between the amount of moisture absorbed and the void-growth at interface since different materials have different k . Some failures may occur for materials with minor moisture absorption (low C), but the material has very high k . Some other materials do not fail, even with major moisture absorption (very high C), due to the excellent resistance of interface strength at high moisture concentration and high temperature (very low k). However, for some material the correlation between the delamination and the moisture absorption is direct and obvious. Therefore, (9) is a general form to describe the void behavior on interface.

The exact determination of the material properties such as k is challenging. Instead of determining (9), in the following, the solution for a single void will be applied to see how much void growth in stage 2 will lead the void grow unstably. Let assume that the initial void volume fraction is 0.01. At the beginning the void will deform along the solid line shown in Fig. 10. Then void growth enters second stage, in which the stress-level does not change but void grows following (9). This stage is shown in Fig. 9 as dotted line, which will intersect with another equilibrium curve. The void will not grow further if stress-level is still

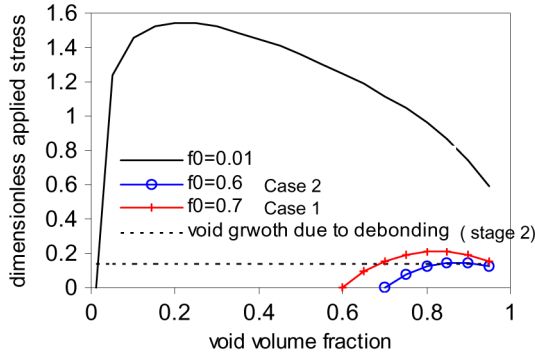


Fig. 10. Void growth at interfaces.

below the critical stress. Otherwise, like case 2 shown in Fig. 9, the delamination will take place.

The micromechanics analysis based on the single-void model study reveals some fundamental features associated with the failure mechanism for porous material such as the unstable growth of voids [13], [22]. How to link the results of the single void behavior to descriptions of material behavior in a macroscopic sense therefore becomes one of the critical issues. Homogenization processes can be applied for this purpose. There are several theories to establish the relationships between the microscopic and macroscopic variables [23], [24]. For a porous material, the void volume fraction f is treated as a field variable: a damage parameter to represent the local material behavior. $f = 1$ at a particular (continuum) point implies that delamination takes place at this “point.” The evolution equation is required for the void volume fraction f . For homogeneous material in bulk, the growth rate can be written as

$$\dot{f} = \dot{f}_{\text{growth}} + \dot{f}_{\text{nucleation}} \quad (10)$$

$$\dot{f}_{\text{growth}} = (1 - f)\dot{E}_{kk} \quad (11)$$

$$\dot{f}_{\text{nucleation}} = A\dot{\sigma}_e + B\dot{\Sigma}_m. \quad (12)$$

At interface, the impact of interface on void growth should be included

$$\dot{f} = \dot{f}_{\text{growth}} + \dot{f}_{\text{nucleation}} + \dot{f}_{\text{debonding}} \quad (13)$$

$$\dot{f}_{\text{growth}} = (1 - f)\dot{E}_{kk} \quad (14)$$

$$\dot{f}_{\text{nucleation}} = A\dot{\sigma}_e + B\dot{\Sigma}_m \quad (15)$$

$$\dot{f}_{\text{debonding}} = kCe^{-\frac{Q}{RT}}\dot{T} \quad (16)$$

where equation (16) comes from (9), which is only applicable to the interface. The detailed results using these equations with finite element implementation will be reported in a separate paper.

VI. CONCLUSION

When ambient temperature and humidity vary with time, such as reflow process, the thermal-moisture analogy in moisture diffusion will not be valid. A special treatment must be considered to perform the moisture diffusion modeling correctly. This paper then proceeds to a whole field vapor pressure analysis based on a multiscale vapor pressure model and moisture diffusion. Results show that vapor pressure is saturated in a very early stage of moisture absorption for a flip chip package. It

implies that for most cases, regardless of moisture absorption, vapor pressure for different materials may always remain the same saturation level. Therefore, the moisture sensitivity performance of a flip chip package does not necessarily correlate to the moisture absorption of underfill. The experimental results presented in this paper confirm that the adhesion in the presence of moisture at elevated temperature is the only parameter for underfills to control package moisture sensitivity performance. A mathematical description and a framework to define the interface strength based on a micromechanics approach is also presented in this paper.

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