Mechanism Analysis for Moisture-Induced Failure in IC Packages

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ABSTRACT

The moisture-induced delamination in IC packages is considered as the consequence of the rapid nucleation and growth of the microvoids or microcracks at interfaces during the reflow soldering. Therefore, the representative volume element (RVE) approach, by which the micro-void effect can be taken into consideration, is introduced in this paper. A theoretical model is established to calculate the vapor pressure generated anywhere in plastic materials during reflow. A delamination criterion is postulated, in which two parameters are introduced, namely, the internal vapor pressure, and the local void volume fraction, respectively. The vapor pressure behaves as an external loading at interfaces when delamination takes place. A method is provided to estimate the initial vapor pressure at delaminated area by the extension of the model developed here. A rigid-plastic model is adopted to analyze the package bulging, and the limit pressure that leads the package to collapse is obtained.

Keywords: IC package, moisture, delamination, bulging, cracking, vapor pressure, and criterion.

1. INTRODUCTION

Package popcorning, a moisture-induced failure, is a common phenomenon that occurs during the surface mounting onto the printed circuit board by means of high-temperature reflow soldering. Such failures are usually attributed to high internal pressures caused by sudden evaporation of moisture, absorbed by the plastic materials [1,2]. Fig.1 illustrates this failure mechanism. Popcorn package cracking is generally believed to progress over four stages. At stage 1 (preconditioning), the plastic materials in package absorb moisture from the environment, which condenses in micropores in these materials. Consequently, the interfacial adhesion strength is degraded, in particular, at high temperature level. At stage 2, the condensed moisture is vaporized when the temperature rises during reflow, creating high internal vapor pressure inside of package. Upon the vapor pressure along the interfaces exceeding the adhesion strength, the micro-voids or defects along the interfaces will grow and nucleate rapidly to result in the delamination. The vaporizing moisture instantaneously exerts a pressure as traction loading at the delaminated interfaces, which aggravates the delamination and causes the package to bulge at stage 3. Eventually the package crack forms that may propagate laterally outwards (stage 4). When the crack reaches the package exterior, high-pressure water vapor is suddenly released, producing an audible sound like popcorning. The popcorn failure was first postulated by Fukuzawa et al in 1985 [1], and shortly, supported by numerous findings and publications (see, e.g. ref.2-5, 12-14).

Since the package cracking is controlled by the local moisture concentration at the critical interfaces rather than the absolute water gain in the package, the moisture diffusion modelling is needed to understand the moisture distribution over the entire package. Perhaps the ultimate goal of the moisture diffusion modelling is to calculate the vapor pressure and its distribution within the material during reflow, and to relate this to the initiation of delamination at interfaces. Previous researchers [3-5] assumed that the delamination exists before the reflow, and considered the vapor pressure as traction loading subjected to the delaminated interfaces. Since the vapor pressure is generated anywhere in the package, it is necessary to investigate the whole-field vapor pressure distribution before the package delamination.

The objectives of this study attempt to provide a quantitative analysis on the mechanism of the delamination caused by moisture vaporization. In the subsequent section, the moisture diffusion analysis is briefly reviewed, with a one-dimensional analytical solution showing the nature of the moisture diffusion. In section 3, the micromechanics approach is introduced and a theoretical model for the calculation of vapor pressure is developed. In section 4, a delamination criterion is postulated, in which two parameters are introduced, namely, internal vapor pressure, and the local void volume fraction, respectively. In section 5, the vapor pressure that exerts on the delaminated surfaces is estimated by the extension of the model developed in section 3. Finally, a rigid-plastic model is introduced to analyze the package bulging, and the limit pressure that leads the package to collapse is obtained.
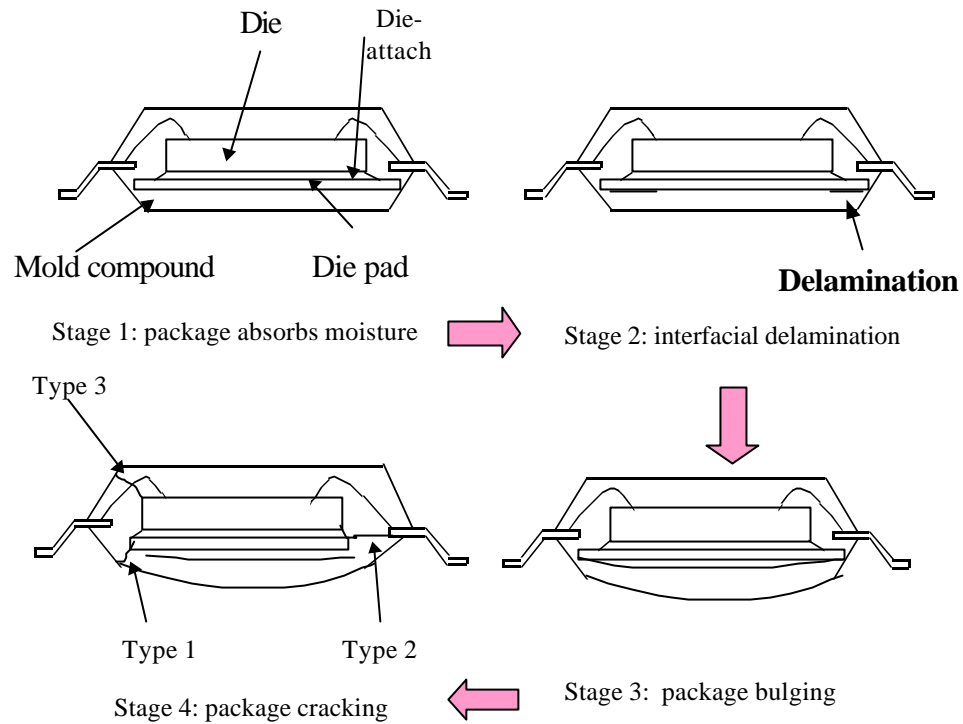
Fig.1 Package delamination and cracking caused by moisture

2. MOISTURE DIFFUSION ANALYSIS

Transient moisture diffusion follows Fick's law as following

$$\frac{\partial^2 C^2}{\partial x^2} + \frac{\partial^2 C^2}{\partial y^2} + \frac{\partial^2 C^2}{\partial z^2} = \frac{1}{a_D}\frac{\P C}{\P t} \qquad (1)$$

where C is the local concentration (g/cm^3, weight of water or water vapor per unit volume in bulk material), x,y,z are co-ordinates (cm), a_D is the moisture diffusivity (cm^2/s), and t is the time (s). Across the bimaterial interface, the continuity conditions are assumed as

$$C_1 / S_1 = C_2 / S_2 \qquad (2)$$

$$a_{D1}\frac{\partial C_1}{\partial n} = a_{D2}\frac{\partial C_2}{\partial n} \qquad (3)$$

where the subscripts 1 and 2 represent different materials respectively, and S is the solubility. The solubility S is related to the saturated concentration C_{sat} by

$$S = C_{sat} / p_{ext} \qquad (4)$$

p_{ext} is the ambient vapor pressure under the given humid conditions. Therefore, the alternative quantities can be defined with continuity across the interface, as following

$$\boldsymbol{j} = C / S \qquad (5)$$

or equivalently, by equation (4) [6]

$$w = C / C_{sat} \qquad (6)$$

$$\partial C(x,t)/\partial x\big|_{x=h} = 0$$

$$h = 0.2\text{cm}$$

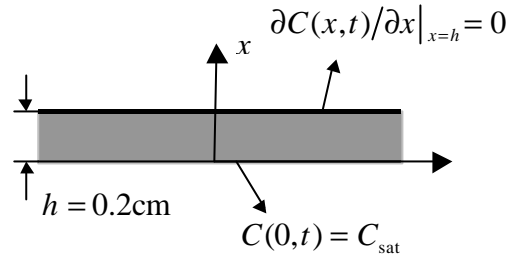$$C(0,t) = C_{\text{sat}}$$

Fig.2 One-dimensional transient moisture diffusion problem

In order to illustrate the nature of the moisture diffusion in plastic materials, we consider an example of a simple transient moisture diffusion problem in a slab, with the boundary conditions as shown in Fig.2. The thickness of 2mm is taken as a typical value. The material properties (e.g. a typical mold compound), together with the ambient humid conditions for three types of moisture preconditioning are listed in Table 1[7]. The solution can be represented as [8]

$$C(x,t) = C_{\text{sat}}[1 - \sum_{n=0}^{\infty} \frac{[2(-1)^n]e^{-l_n^2 a_D t / h^2}}{l_n} \cos(l_n(h-x)/h)] \qquad (7)$$

where

$$l_n = (\frac{2n+1}{2})p \qquad (8)$$

Fig.3 plotted the results for the local moisture concentration at $x=h$ as the function of time. For level 3(30°C/60%RH), the slab is far from the saturated after 500 hours. The nearly saturated state is reached for level 2 (85°C/60%RH) and level 1 (85°C/85%RH), respectively. It would be interesting to compare these results with the transient heat conduction in the same material configuration, with the thermal diffusivity as 4.22×10^{-3} cm^2/s [5], when the side $x=0$ is suddenly subjected to a step-temperature-rise ΔT. Fig. 4 showed that the heat transfer is much faster than moisture diffusion. This implies that the package temperature can be assumed uniform at reflow temperature. The loss of moisture due to desorption during the process of reflow is negligible, as the solder reflow process is completed in a few minutes.

Table 1 Three types of moisture preconditioning

| Moisture preconditioning	Saturated vapor density r_g (g/cm³)	Saturated vapor pressure p_g (MPa)	Ambient vapor density r_{ext} (g/cm³)	Ambient vapor pressure p_{ext} (MPa)	Thermal diffusivity a_D (cm²/s)	Saturated concentration C_{sat} (g/cm³) $= p_{ext}S$
30°C/60%RH	3.04×10^{-5}	4.24×10^{-3}	$0.6\,r_g$	$0.6\,p_g$	3.13×10^{-9}	7.86×10^{-3}
85°C/60%RH	3.58×10^{-4}	5.87×10^{-2}	$0.6\,r_g$	$0.6\,p_g$	2.85×10^{-8}	8.84×10^{-3}
85°C/85%RH	3.58×10^{-4}	5.87×10^{-2}	$0.85\,r_g$	$0.85\,p_g$	2.85×10^{-8}	1.25×10^{-2}
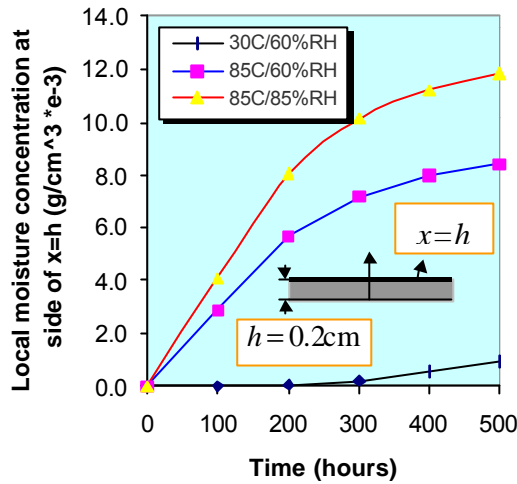
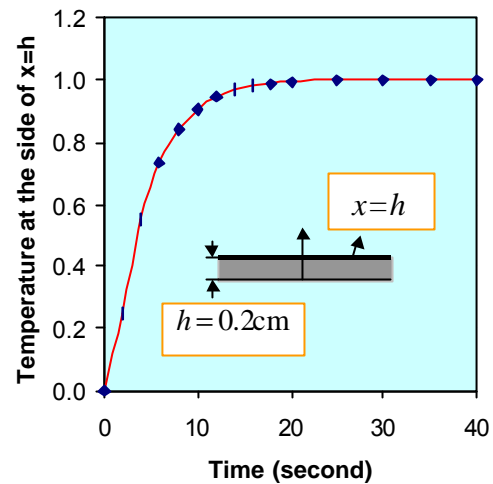Fig.3 Local moisture concentration at $x=h$ as function of time

Fig.4 Temperature at $x=h$ as function of time

3. MOISTURE VAPORIZATION DURING REFLOW

A difference in a few orders exists between the saturated moisture concentration (C_{sat}) and the corresponding saturated ambient water vapor density (e.g. $\mathbf{r}_g$ at 85°C/85%RH) for plastic materials such as mold compound (see Table 1). This suggests that the moisture absorbed by plastic materials has to be condensed into water in the microvoids (or free-volume) of materials. During the reflow soldering, the temperature rises and the moisture vaporizes to produce high internal pressure. The vapor pressure, however, will maintain its saturated pressure (the saturated pressure increases with the temperature) as long as the moisture in voids is not fully vaporized.

Representative Volume Element (RVE) Approach In order to estimate the vapor pressure generated inside of the material, the Representative Volume Element (RVE) approach is introduced here. Let's take a very small representative material sample, termed RVE as shown in Fig.5 [9]. From the microscopic level, the RVE is large enough to be statistically representative of the material properties at this location. Therefore, *a field quantity*, the void volume fraction f, can be defined as

$$f = \frac{dV_f}{dV} \tag{9}$$

where dV_f is the void volume and dV is the element volume. The f should satisfy $0 \le f \le 1$. f=1 (fully voided) implies delamination occur at this location. The micro voids are distributed randomly but uniformly in material, thus the initial void volume fraction, f_0, is a material property. Due to the weak interfacial adhesion strength, the voids may be evolved much faster at interfaces than those inside of materials during loading. Thus the delamination may take place at interfaces where the void volume fraction f becomes 1 (the void volume fraction inside of material does not change much).

A useful quantity, the moisture density in the voids, can be introduced as

$$\mathbf{r}_m = \frac{dW_m}{dV_f} = \frac{dW_m / dV}{dV_f / dV} = \frac{C}{f_0} \tag{10}$$
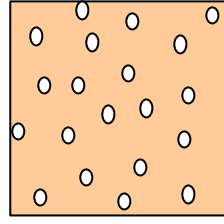
Fig.5: a representative volume element (RVE)

where dW_m is the moisture weight in a RVE. Further, ***the transition temperature T_1*** can be defined, at which the moisture in voids is fully saturated in vapor phase, as following

$$\boldsymbol{r}_m(x_i, T_0) = \boldsymbol{r}_g(T_1) \tag{11}$$

where ρ_g is the saturated vapor density at temperature T_1 ,and T_0 is the preconditioning temperature at which the moisture is absorbed.

Vapor Pressure Modeling Assume that the vapor gas will satisfy the ideal gas law when all moisture becomes vaporized. Three different situations are identified according to the local moisture concentration after preconditioning. In the first situation, the moisture density in voids is low enough so that all moisture becomes vaporized at preconditioning temperature T_0 ($T_1 \leq T_0$). In the second situation, the moisture is fully vaporized at a temperature between preconditioning temperature T_0 and peak reflow temperature T ($T_0 \leq T_1 \leq T$). For the last case, the moisture is not fully vaporized even at reflow temperature T ($T_1 \geq T$). Therefore, the vapor pressure generated at reflow temperature can be calculated from following equations for three different cases, respectively

$$p = \frac{C\, p_g(T_0)T}{f\, T_0} \qquad \text{when } T_1 \leq T_0 \tag{12}$$

$$p = \frac{p_g(T_1)T}{T_1} \qquad \text{when } T_0 \leq T_1 \leq T \tag{13}$$

$$p = p_g(T) \qquad \text{when } T_1 \geq T \tag{14}$$

where p_g are the saturated vapor pressure.

Initial Volume Fraction of Voids In the following an approximate method is provided to estimate the initial void volume fraction. According to equation (10), when saturated, the local concentration C is replaced by C_{sat}. Thus the initial void volume fraction can be expressed as following

$$f_0 = \frac{1}{\boldsymbol{r}_m} C_{sat} = \frac{1}{\boldsymbol{r}_m} \boldsymbol{r}_{ext}\boldsymbol{y}_0 \exp(Q_y / RT) \tag{15}$$

Since, $\boldsymbol{r}_m < 1.0\text{g/cm}^3$, we have

$$f_0 > C_{sat}\big|_{100/100} = \boldsymbol{r}_g\boldsymbol{y}_0 \exp(Q_y / RT)\big|_{100/100} \tag{16}$$

Equation (16) provides a simply way to predict the approximate magnitude of the voids existing in materials. It is a low-bound estimation since the moisture will be in the mixture of water and vapor in voids. Table 2 lists the results of the initial void volume fraction for some common used plastic materials in IC packages by equation (16), according to the material property data measured by [4]. It showed that the fractions are usually between 1% and 5 %.

Table 2 Initial void volume fraction for some materials in IC packages

Material	BT	Die-attach	Mold compound	Solder mask
f_0 (%)	3.46	3.29	1.46	5.05

Example As an example of vapor pressure induced by moisture, the homogenous slab used in last section is considered here. Three kinds of different moisture pre-conditioning are applied respectively. Fig.6 plotted the results of the vapor pressure at side $x=h$ at temperature 220°C, as function of the preconditioning time. It showed that, although the material at the side $x=h$ is far from the saturation at time $t=273$, 29.0, and 26.3 hours for level 3, 2 and 1 respectively (see Fig.3), the vapor pressure has reached its saturated pressure and maintains unchanged, whenever more moisture is absorbed.

It is interesting to take an extreme case, where the material is nearly hollow, which means f_0 is nearly equal to 1. The material is assumed to be fully saturated at 85°C/85%RH condition. From equation (11), the transition temperature T_1 is 225°C. This suggests that the peak pressure (saturated pressure) at interfaces is actually not very sensitive to the initial void volume fraction. It also implies that the moisture at the interfaces can not be vaporized completely until delamination. It must be emphasized, however, that the local void volume fraction at interfaces affects the delamination behavior greatly though vapor pressure does
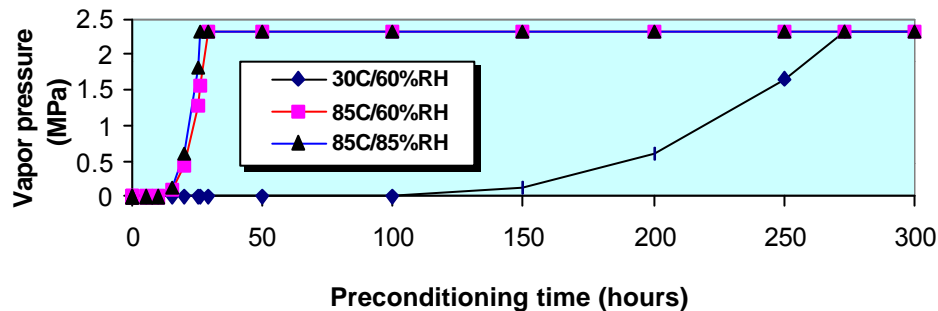

Fig.6 Vapor pressure at 220°C on the side of $x=h$ for a slab, subjected to three different types of preconditioning, as function of preconditioning time

not change. This is because that, with increase of void volume fraction, the moisture density defined by equation (10) will increase correspondingly, thus the adhesion is degraded greatly. The unstable growth of voids are also affected by the local void volume fraction.

Vapor Pressure-Induced Expansion The above example concludes that the vapor pressure saturated much faster than moisture. This implies that the vapor pressure may be uniformly distributed in the plastic material regardless of moisture saturation. The Young's modules of plastic material drops a few orders at reflow temperature, thus the vapor pressure-induced expansion may become as important as thermal expansion. For instance, assume the Young's modulus of a typical underfill at 220°C is 0.5 GPa. Therefore, the volume change caused by vapor pressure can be estimated as

$$\frac{\Delta V}{V} = \frac{1-2\boldsymbol{n}}{E}\, p = 2.784\, e - 3$$

which, is comparable with thermal expansion. It concludes that the vapor pressure-induced expansion introduces additional mismatch. It must be pointed out that such an expansion is directly related to the vapor pressure distribution, rather than moisture distribution.

4. DELAMINATION CRITERION

During reflow soldering, the entire package will be heated to the temperature as high as 220°C. The saturated vapor pressure at this temperature is 2.32MPa. It has been shown before, that the pressure will reach its saturated pressure even though less moisture is absorbed. This means that it is not sufficient to use the maximum vapor pressure only as indicator to predict the delamination. In the following, a study on the critical delamination conditions during the reflow soldering is presented.

The necessary critical condition for the delamination can be proposed as

$$p \text{ at soldering temperature} \geq \boldsymbol{s}_R \text{ at soldering temperature} \qquad (17)$$

where p is the vapor pressure and $\boldsymbol{s}_R$ is the critical interfacial adhesion *strength **in terms of pressure loading***. Equation (17) implies that the interfacial adhesion strength is a key element for delamination prediction. Equation (17) may be proposed in other forms, in terms of tensile/shear stresses or stress intensity factors (mode I and II). Here $\boldsymbol{s}_R$ in terms of vapor pressure is introduced, since the vapor pressure can be exactly predicted and other effect such as thermal stresses can be considered as pre-stress condition.

The adhesion strength is degraded with the increase of moisture absorption, though the vapor pressure maintains its saturated value. When the adhesion strength is reduced to the level below the vapor pressure, the voids start to grow up. The vapor pressure inside of the voids will decrease greatly if no sufficient moisture continues to vaporize. In order to know the maximum void volume fraction, until which the saturated vapor pressure is maintained, the ideal gas law is applied to a RVE as following

$$p\mathrm{d}V_f = \mathrm{d}W_m RT \qquad (18)$$

or, equivalently, divided by dV, the volume of the RVE ,

$$pf = CRT \qquad (19)$$

where f is the local void volume fraction, and C is the local moisture concentration. Denote f_s as the maximum void volume fraction to keep its saturated pressure $p = p_g$. Thus f_s can be calculated from equation (19) as follows

$$f_s = CRT / p_g \qquad (20)$$

When voids start to grow up and f_s exceeds 1.0, the delamination occurs. There is another situation where delamination takes place with $f_s < 1.0$. This means the void-growth becomes unstable if the void volume fraction exceeds a certain value. Therefore, a supplementary critical condition for the delmaination can be proposed as

$$f_s \geq f_R \qquad (21)$$

where f_R is the critical value for unstable void growth. In order to illustrate this, the experimental results obtained by [3] and [4] are analyzed here. Galloway et al.[4] conducted a moisture-resistance test for 68 I/O PBGA. The critical local concentration for the die-attach used are 0.0095g/cm^3. From equation (19), one finds $f_s = 0.678$. In Kitano et. al.'s work [3], it was found that the critical moisture concentration at the interface between die-pad and mold compound is 0.0068g/cm^3, which corresponds to $f_s = 0.586$.

It seems that the critical value f_R for unstable void growth is around 0.6. This ratio, however, is material dependent. The theoretical determination of f_R through the voiding instability analysis is possible. Huang et al [10] presented a model study of voiding for a finite solid that contains a void. Further efforts are needed to consider a void at interface. Besides, the effect of the remote-field deviatoric stress should be addressed in future study to understand the thermal stress effect on moisture induced failures.

Equation (20) can be further simplified as

$$f_s = C / \rho_g \tag{22}$$

from which it can be seen that f_s is simply a ratio of the local concentration over the saturated water vapor density at soldering temperature.

5. VAPOR PRESSURE AS EXTERNAL LOADING IN DELAMIANTATED AREA

The internal vapor pressure inside of the voids at the interfaces instantaneously become an external pressure subjected to the delaminated interfaces when delamination is formed at reflow. As a natural extension of the model developed in section 3, the initial vapor pressure as traction loading at interfaces can be estimated by setting the final void volume fraction f=1. Based on three different situations mentioned before, the initial vapor pressure at the interface gap can be calculated from the following, respectively,

$$p = \frac{C p_g(T_0) T}{T_0} \quad \text{when} \quad T_1 \leq T_0 \tag{23}$$

$$p = \frac{p_g(T_1) T f_0}{T_1} \quad \text{when} \quad T_0 \leq T_1 \leq T \tag{24}$$

$$p = \begin{cases} p_g(T) & C / \rho_g(T) \geq 1 \\ C p_g(T) / \rho_g(T) & C / \rho_g(T) < 1 \end{cases} \quad \text{when} \quad T_1 \geq T \tag{25}$$

For the first and second cases by equations (23) and (24), respectively, the vapor pressure is much less than its saturated pressure. Thus the delamination may never occur. It may be concluded that the equation (25) is a widely used equation to estimate the vapor pressure in the gap.

As we know, the vapor pressure at the delaminated area will be immediately uniform when the delamination is complete, although the local moisture concentrations at interfaces are different with the location. The average local concentration is therefore defined as following

$$C^{ave} = \frac{\int_A C dA}{A} \tag{26}$$

where A is the delaminated area. When using above equations, the concentration C should be replaced by C^{ave}.

6. A RIGID-PLASTIC MODEL FOR PACKAGE BULGING ANALYSIS

The vapor pressure subjected to the delaminated area will cause the package to bulge. The plastic materials at reflow temperature become very compliant and soft. Therefore, the material can be treated as rigid-plastic or perfectly elasto-plastic material. For example, in

the conventional package, when the delamination is complete between die-pad and mold compound, the mold compound under the die-pad can be assumed as a plate with all edges clamped (see Fig.7), subjected to a pressure on the top of the plate. According to the plasticity theory, the limit pressure can be estimated by following equation (see, e.g. ref.[11])

$$p^* = \frac{3s_s h^2}{L^2} \qquad\qquad (27)$$

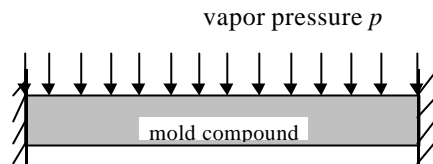vapor pressure p

mold compound

Fig.7 mold compound under die-pad as a clamped plate
after delamination

where h is the thickness of the mold compound under the die-pad and the L is the length of the interface. Such a condition can be regarded as a critical cracking condition, since the edge of the plate becomes plastic hinge (see Fig.8(a)). From this relation, it can be found that reducing the die-pad size (L) or increasing the thickness of the mold compound (h) can enhance the loading capacity of the package. Besides, the yielding stress is an important property for the cracking resistance.

The rigid-plastic model provides a more realistic analysis on the package deformation after the delamination. However, this analysis may not be accurate enough, since the traditional plate theory and the small-deflection assumption are adopted. With the bulging increasing, the membrane effect becomes increasingly as important as bending effect. The combination of the membrane and bending effects will result in a completely yielding stress state at the edge of the plate, as shown in Fig.8(b). Therefore, a large-deflection analysis considering the membrane effect is necessary in future study.

σ_s

$-\sigma_s$

σ_s

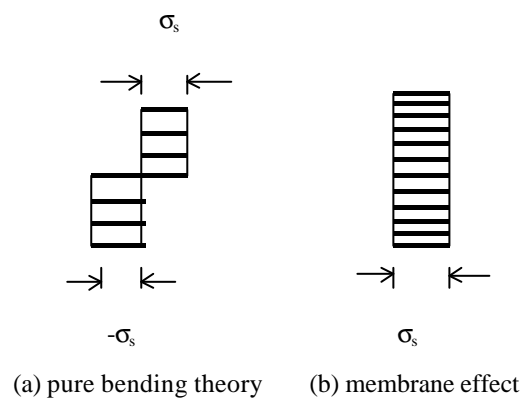(a) pure bending theory   (b) membrane effect

Fig.8 stress state at the edge of the clamped plate (a):
bending theory (b): membrane effect

7. CONCLUSIONS

In order to understand the failure mechanism caused by moisture, the moisture diffusion modelling is needed to predict the local moisture concentrations at interfaces. It was found

that the moisture density inside of the plastic material is much dense than the ambient humidity (e.g. 85°C/85%RH). This implies that the moisture has to be condensed in plastic materials. Such an amount of moisture may not be fully vaporized at reflow temperature. Therefore, the saturated vapor pressure (2.32MPa) is reached, even though less moisture is absorbed. The vapor pressure introduces additional mismatch in package. Such a mismatch is directly related to the vapor pressure distribution, rather than moisture distribution. It demonstrated that it is not sufficient to use the maximum vapor pressure only as indicator to predict the delamination. More importantly, the interfacial adhesion strength will be degraded with moisture absorption. A two-parameter delamination criterion is proposed in this paper, in which the local void volume fraction is introduced. It is pointed out that it may be possible to get the critical void volume fraction by voiding instability analysis. When the delamination takes places, the internal vapor pressure inside of the voids at the interfaces becomes an external pressure subjected to the delaminated surfaces. This vapor pressure can be estimated based on the model developed in this paper. A rigid-plastic model is introduced to analyze the package bulging, and the limit pressure that leads the package to collapse is obtained. The impact of the large-deflection effect on the package bulging is highlighted.

REFERENCES

1. Fukuzawa, S. Ishiguro, and S. Nanbu (1985), Moisture resistence degradation of plastic LSI's by reflow soldering, *Proc. IRPS*, 192-197

2. A.A. Gallo and R. Munamarty (1995), Popcorning: a failure mechanism in plastic-encapsulated microcircuits, *IEEE Transactions on Reliability*, **44**(3), 362-367

3. M.Kitano, A. Nishimura, and S.Kawai (1988), Analysis of package cracking during reflow soldering process, *Proc. IRPS,* 90-95

4. J.E. Galloway and B.M. Miles (1997), Moisture absorption and desorption predictions for plastic ball grid array packages, *IEEE Tranasction on Component,Packaging, and Manufacturing, A,* **20**(3), 274-279

5. A.A.O Tay and T Lin (1996), Moisture diffision and heat transfer in plastic IC packages, *IEEE Tranasction on Component,Packaging, and Manufacturing, A,* **19**(2), 186-193

6. E.H. Wong and T.B.Lim (1997), Moisture diffusion and vapor pressure modeling in IC packages, *48th ECTC*

7. JEDEC Standard (1994), Test method A 112, Moisture induced stress sensitivity for plastic surface mount devices, Electronic Industries Association

8. B.Gebhart (1993), *Heat Conduction and Mass Diffusion,* New York, McGraw Hill

9. A.L. Gurson (1977), *ASME Journal of Applied Mechanics*, **99**,2

10. Huang,Y, Hu K.X., Yeh, C.P., Li,N-.Y, Hwang K.C., (1997), A model study of thermal stress-induced voiding in electronic packages*, ASME Journal of Electronic Packaging*, **118**, 229

11. T.-X. Yu (1990), *Plasticity*, Higher Education Press, Beijing.

12. L.T. Nguyen, K.L. Chen and J. Schaefer, et al, (1995), A new crierion for package integrity under solder reflow conditions, IEEE 45th ECTC, 478-490

13. M.G. Pecht, L.T. Nguyen and E.B. Hakim (1995), Plastic Encapsulated Microelectronics: materials, process, quality, reliability and applications, John Wiley & Sons.

14. E.Suhir (1995), Predictedfailure criterion for moisture-sensitive plastic packages, ECTC 1995.

15. Sheng Liu & Yuhai Mei (1995), behavoir of delaminated plastic IC packages subjected to encapsulation cooling, moisture absorption, and wave soldering, IEEE Trasactions of Compoents, Packaging, and Manufacturing Technology, part A, 18(3), 634-645.