Handling of Highly-Moisture Sensitive Components - An Analysis of Low-Humidity Containment and Baking Schedules

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Abstract

Unique component handling issues can arise when an assembly factory uses highly-moisture sensitive surface mount devices (SMDs). This work describes how the distribution of moisture within the molded plastic body of a SMD is an important variable for survivability. JEDEC/IPC [1] moisture level rated packages classified as Levels 4-5a are shown to require additional handling constraints beyond the typical out-of-bag exposure time tracking. Nitrogen or desiccated cabinet containment is shown as a safe and effective means for long-term storage provided the effects of prior out-of-bag exposure conditions are taken into account. Moisture diffusion analyses coupled with experimental verification studies show that time in storage is as important a variable as floor-life exposure for highly-moisture sensitive devices. Improvements in floor-life survivability can be obtained by a handling procedure that includes cyclic storage in low humidity containment. SMDs that have exceeded their floor-life limits are analyzed for proper baking schedules. Optimized baking schedules can be adopted depending on a knowledge of the exposure conditions and the moisture sensitivity level of the device.

Introduction

Issues of handling and storage of moisture sensitive ICs generally have not been fully treated in the literature [2,3]. Most handling issues that are discussed reference the IPC specification IPC-SM-786A [4], which unfortunately contains only cursory information about the moisture diffusion aspects for moisture sensitive ICs. The IPC document states that safe long-term storage can be achieved by maintaining an ambient relative humidity below 20%. The specification also suggests that floor life is essentially an additive function, e.g., a moisture sensitive device exposed for one day and placed into a low humidity storage is considered to have essentially one less day of floor life remaining no matter how long it is stored in the low humidity environment. This reasoning unfortunately has incorrectly assumed that moisture diffusion is abated by merely placing a moisture sensitive SMD into a low humidity environment. It will be shown that any perturbation of moisture exposure will diffuse and redistribute within the mold compound continuously even during subsequent storage of devices. Because of this continuous redistribution of ingressed moisture, highly-moisture sensitive SMDs are potentially at risk if given partial floor-life exposures and then placed into storage for board assembly at a later date. The extent of the risk will depend on both the length of the floor-life exposure and the time in storage. Moisture/reflow damage will therefore be dependent on the redistribution of moisture during both these exposure events.

The objective of this paper is to show how perturbations of moisture exposure followed by storage containment can affect the reflow performance of highly-moisture sensitive SMDs. Diffusion analyses are used to show that moisture will diffuse and redistribute during storage after an initial floor-life exposure. Experimental moisture/reflow studies are presented that provide verification for the storage containment issue. A similar analysis is carried out for moisture diffusion during high temperature dry baking. Diffusion analyses coupled with moisture/reflow testing are presented for optimized baking schedules. These studies will show that inadequate baking times can in fact drive more moisture into critical internal interfaces resulting in increased risk for moisture/reflow damage.

Theory

Several key assumptions are used to model the diffusion behavior. First, it is assumed that Henry’s Law is the driving force for moisture ingress, e.g., the solubility of moisture in the mold compound is proportional to the partial pressure of water vapor in the surrounding ambient environment [5]. This thermodynamic process is considered reversible and therefore applicable for both absorption and desorption. Next, it is assumed that the moisture diffusivity in mold compounds is constant and independent of concentration. Finally, it is assumed that the degree of moisture/reflow damage is controlled by the amount of moisture that accumulates at key internal interfaces. This interface concentration criterion has been successfully used and shown effective in several previous studies [6-8].

Solving Fick's equations [9]:

$$J = -D\frac{\partial C}{\partial x} \tag{1}$$

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{2}$$

where C is the moisture concentration in mg/cm^3, D the diffusivity (cm^2/sec), J the flux, t is time, and x the spatial plastic thickness. Taking x=0 as the spatial assignment for the buried interface with a plastic thickness of x =*L*, a solution is sought that satisfies the following boundary conditions:

$$C = 0 \quad \text{at} \quad 0 \le x \le L \quad \text{for} \quad t = 0 \qquad (3)$$

$$C = C_{Sat} \quad \text{at} \quad x = L \quad \text{for} \quad t > 0 \qquad (4)$$

$$D\frac{\partial C}{\partial x} = 0 \quad \text{at} \quad x = 0 \quad \text{for} \quad t > 0 \qquad (5)$$

where C_{Sat} is the equilibrium saturation limit for the mold compound governed by Henry's Law as mentioned earlier. A particular solution satisfying these boundary conditions is found to be [10] :

$$C(x,t) = \frac{2}{L}\sum_{n=0}^{\infty}\left\{ e^{-D(2n+1)^2\pi^2 t/4L^2}\cos\left(\frac{(2n+1)\pi x}{2L}\right)\bullet \left[\frac{(2n+1)\pi D(-1)^n}{2L}\int_0^t e^{D(2n+1)^2\pi^2\lambda/4L^2} C_{Sat}(\mathrm{T}(\lambda),\mathrm{RH}(\lambda))d\lambda\right]\right\} \qquad (6)$$

Using equation (6), we now set about to determine the amount of moisture that accumulates at the buried internal interfaces during partial floor-life exposures and how this moisture re-distributes within the mold compound during storage containment.

Dry Storage

For dry storage containment let us consider the two following exposure scenarios:

Case 1. A PLCC package classified as JEDEC/IPC moisture Level 5 [1], is removed from the dry bag and exposed for 16 hours in an environment of 30°C/60%RH. After this exposure it is then placed into dry storage maintained at 30°C/~0%RH.

Case 2. A similar PLCC package is exposed for 48 hours at 30°C/60%RH and then placed into the 30°C/~0%RH containment.

For both cases consider the moisture diffusivity in the mold compound follows an Arrehenius behavior as shown in equation (7).

$$D(\mathrm{cm}^2/\mathrm{sec}) = 0.0742\exp(-0.42\mathrm{eV}/kT) \qquad (7)$$

It is further assumed that C_{Sat} @ 30°C = 5.3mg/cm^3, and the thickness of mold compound above the die surface is 1.52mm. Also consider that this PLCC was moisture level classified at Level 5 using an exposure of 72 hours at 30°C/60%RH. From this information, the critical interface concentration at the die surface is calculated to be $C_{critial}$ = 0.158mg/cm^3. Using the critical interface criterion [6-8], this amount is now considered the maximum moisture content at the die surface that can be tolerated in order to assure risk free assembly during solder reflow. Any moisture content above this concentration could potentially cause failures. It is also assumed that the device failed Level-4 moisture testing of 96 hours at 30°C/60%RH. This yields an interface concentration of 0.371mg/cm^3 which is the amount now considered to result in moisture/reflow failures.

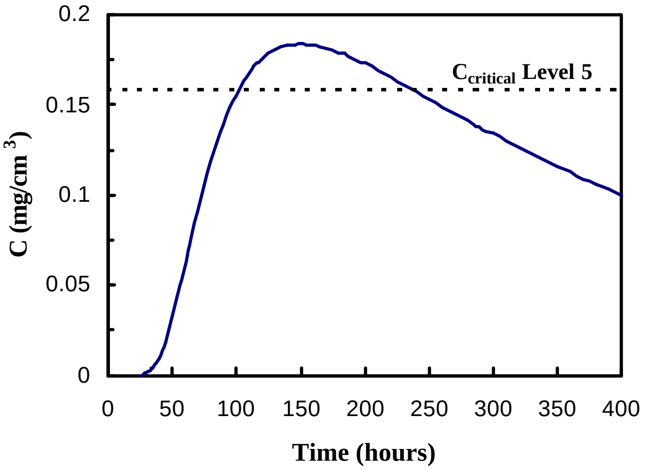

Fig. 1 Concentration at die surface for Case 1.

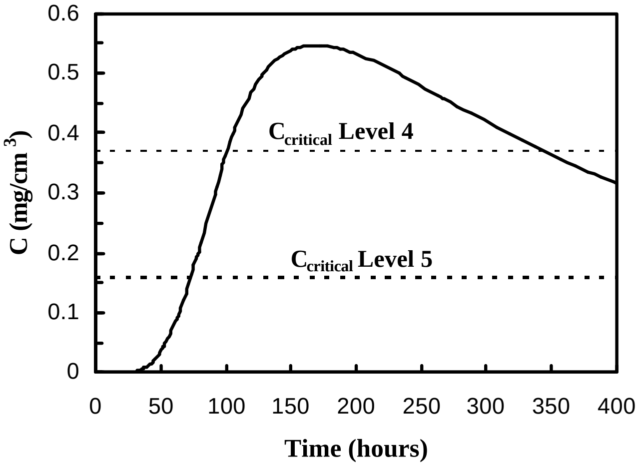

Fig. 2 Concentration at die surface for Case 2.

The calculated interface concentrations for Case 1 and Case 2 are shown in Figures 1 and 2, respectively. For Case 1, the calculations reveal that the initial 16 hour perturbation of moisture exposure continues to diffuse inwards towards the die surface during storage. After 70 hours of storage, the amount of moisture at the interface exceeds the Level 5 $C_{critial}$ value of 0.158mg/cm^3. The interface concentration does not decrease below $C_{critial}$ until a total of 210 hours of storage have elapsed. Any device stored from 70 to 210 hours and then reflowed could have a greater risk for reflow damage.

The probability for failure is even greater for Case 2, see Figure 2. Here the initial 48 hours of moisture exposure has ingressed enough moisture that continued diffusion during storage produces an interface concentration that exceeds the known failing Level 4 critical concentration. Any package reflowed after being in storage from 35 to 285 hours will have a high risk for failure. One will need to wait nearly 640 hours before the interface has dried to a concentration below the passing Level 5 critical concentration.

High Temperature Baking

Dry baking is a potential concern for both the IC supplier and the IC user. Highly-moisture sensitive packages will be baked by the supplier prior to the dry packing process. The intent of the supplier bake is to remove most residual ingressed moisture before sealing devices in dry bags. Generally, a supplier does not want to default to excessively long bake times in order to maintain acceptable component manufacturing cycle times. For a user, dry baking is required whenever the recommended floor-life limits are exceeded. Excessive bake times are again a concern for manufacturing cycle time.

Following a similar analysis as with the dry storage problem, we will again consider test cases for a moisture Level-4 PLCC package in order to highlight the issues with dry baking. Figure 3 shows the die/mold-compound interface concentration after a one week exposure to 30°C/60%RH followed by baking at 125°C/0%RH. The result shows that the interface concentration increases to a maximum after 2 hours of baking and continuously decreases with bake times longer than 2 hours. The interface moisture concentration does not drop below the determined Level 4 $C_{critial}$ amount until after 15 hours of baking and requires a bake time of 21 hours to fall below the Level 5 $C_{critial}$ concentration. This calculation demonstrates that whenever a positive moisture gradient exists within the mold compound, baking will initially force moisture to diffuse inwards towards the die surface before the total gradient can begin to decrease. This occurs because a gradient maximum is created in the through thickness of the mold compound, as shown in Figure 4. By Fick's first Law, moisture cannot diffuse up a concentration gradient, therefore, moisture contained within the mold compound continues to diffuse down this imposed gradient maximum. As the time at bake increases, the gradient maximum moves inwards towards the die surface. The interface concentration cannot decrease until the moving maximum engages the die surface. For this particular case, two hours of baking at 125°C are required for the gradient maximum to impinge the die surface.

After an exposure of 168 hours at 30°C/60%RH, the bake time required to dry the device enough in order to regain an additional safe floor-life performance, is determined to be 18 hours. Figure 5 shows the interface behavior during this process. The user does not have to bake all the moisture out of the package as long as the interface concentration does not exceed $C_{critial}$ during the entire second floor-life exposure. If the device was initially saturated at 60%RH, e.g., C(initial) = 5.3mg/cm^3, a longer bake time of 24 hours will be required to re-establish the floor-life, as shown in Figure 6. Bake times up to 29 hours would be necessary to reset the clock for a device classified as moisture Level 5.

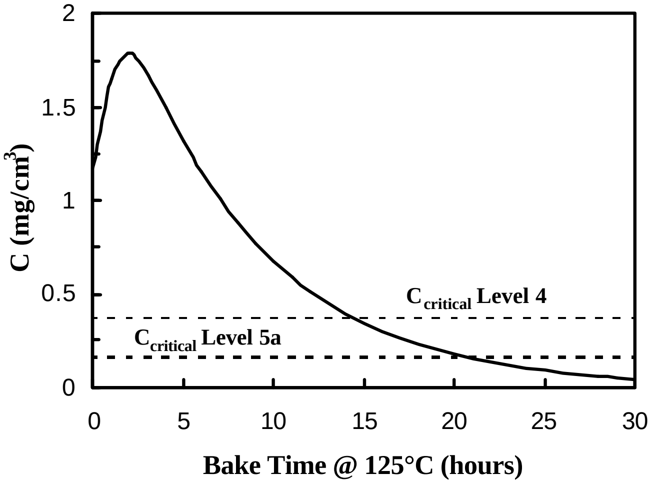

Fig. 3. Concentration at die surface after an initial exposure of 168 hours at 30°C/60%RH followed by baking at 125°C.

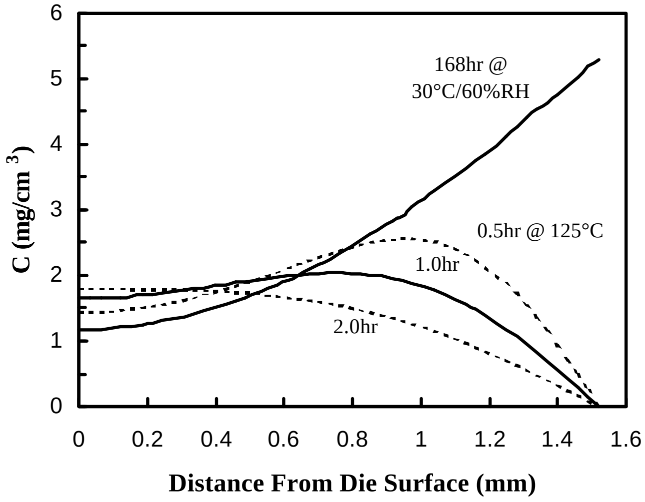

Fig. 4. Moisture gradients produced within the mold compound during baking at 125°C. Initial exposure is 168 hours at 30°C/60%RH.

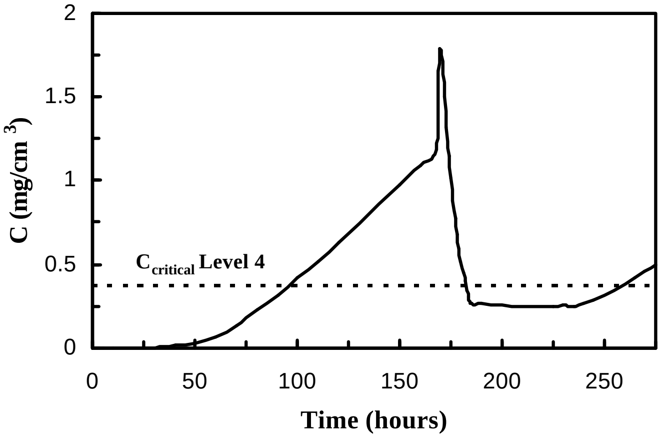

Fig. 5. Concentration at the die surface after an exposure of 168 hours at 30°C/60%RH, baked for 18 hours at 125°C, and followed by a floor life exposure at 30°C/60%RH.

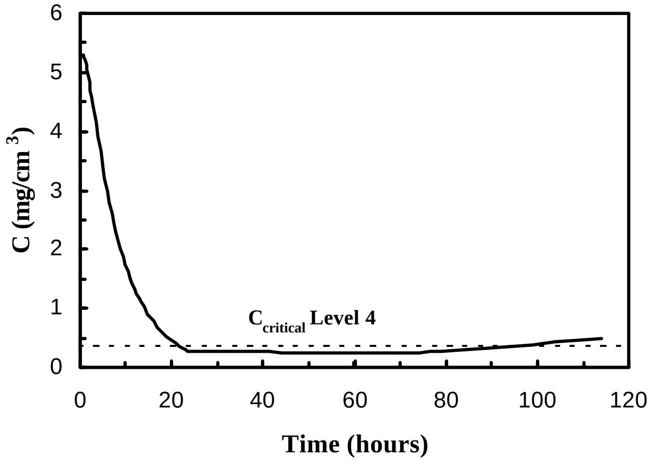

Fig. 6. Concentration at die surface after a saturation exposure to 30°C/60%RH followed by baking for 24 hours at 125°C and then re-exposed to 30°C/60%RH.

Experimental Verification

Dry Storage Containment

To prove the validity of the diffusion analyses, moisture/reflow experiments were performed on a 44-PLCC package known to be highly moisture sensitive. The experimental flow is shown in Figure 7. Initially, all devices were characterized using C-mode Scanning Acoustic Microscopy (C-SAM). The devices were then baked for 72 hours at 125°C to establish a baseline dry package. Dry packaged weights were measured and recorded. After weighing, the packages were immediately placed into a chamber maintained at 30±0.5°C/60%±2%RH. Two exposure times were utilized, 16 hours and 48 hours. After these initial moisture exposures, weight gains were recorded and the devices were then placed into a dry storage containment. Dry storage consisted of a $CaSO_4$ desiccated bell jar that was partially evacuated and then placed into an oven maintained at 30°C. Storage times of 48 hours, 6 days, and 2 weeks were used. After each elapsed storage time, groups of devices were removed, weighed, and convection reflowed to a body surface temperature of 220°C. (The number of devices reflowed per group ranged from 8-20 packages with a median population of 16 devices per cell.) Next, C-SAM imaging was performed and the changes in delamination found at the die/mold-compound interface were recorded. Finally, moisture/reflow performance was also characterized for both moisture Level 4 and Level 5a.

C-SAM imaging of as-received devices indicated that all packages were initially free of delamination. After moisture exposure and reflow, varying amounts of die surface delaminations were observed. A more detailed analysis of the observed delaminations are shown in Figures 8 and 9.

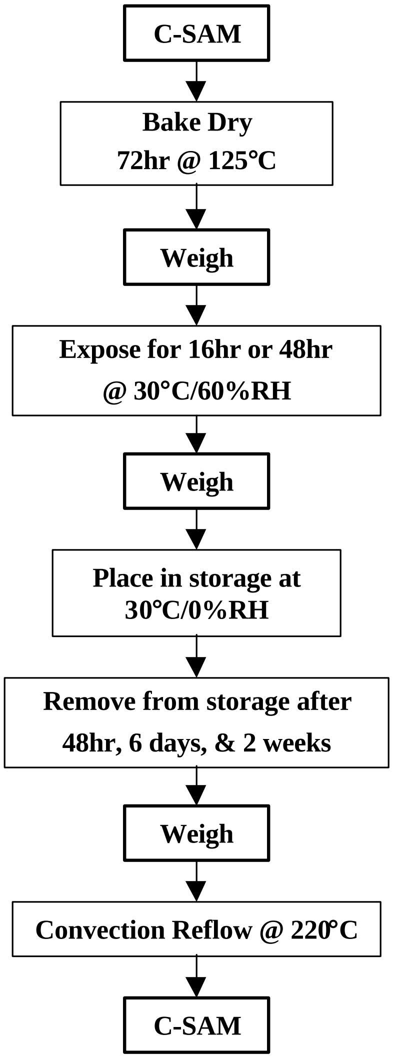

Fig. 7 Experimental flow for dry storage experiment.

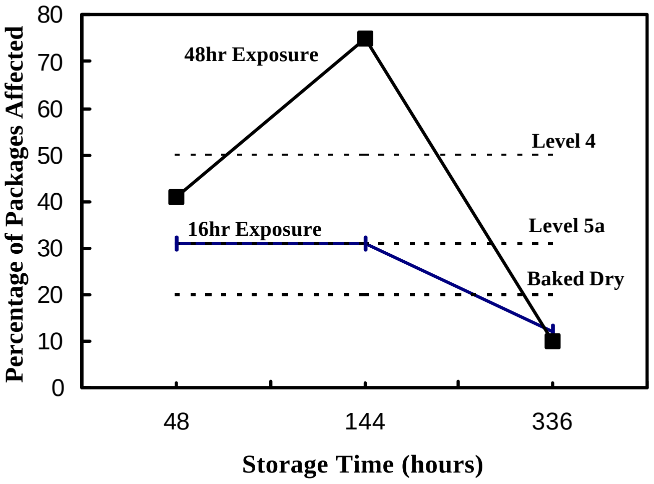

Fig. 8 Percentage of packages with die surface delaminations greater than 5% by area.

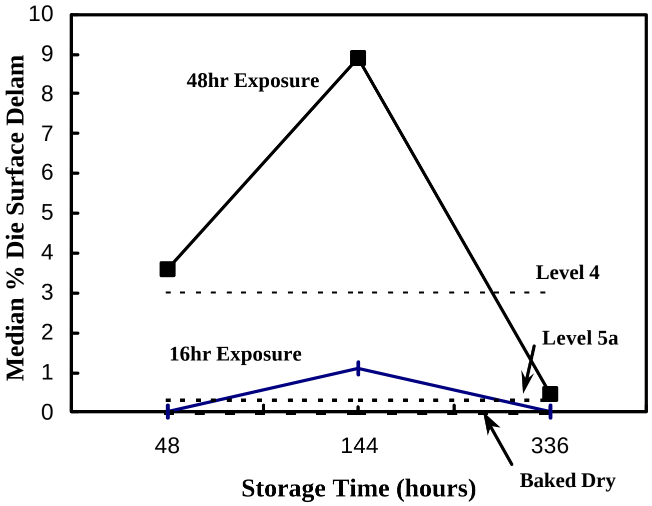

Fig. 9 Median die surface delaminations found for the 16 hour and 48 hour exposure/storage experiment.

Figure 8 shows the total percentage of packages observed to have die surface delaminations greater than 5 area percent for both the 16 hour and 48 hour exposures. This data reveals the maximum reflow damage occurs after a storage of six days for the 48 hour exposed devices. The percentage of delaminated devices is also seen to exceed the total of packages that delaminated during Level 4 testing. These two results tend to support the theoretical predictions that moisture redistribution during storage can lead to delamination failures of highly-moisture sensitive packages. For the 16 hour exposure, a maximum was not found to occur at the six day storage point. There was, however, a decrease in damage response after a two week storage. A plot of the median area percent die surface delaminations are shown in Figure 9. Here the trend supports the predicted maximum damage response found to occur at the six day storage time for both the 16 hour and 48 hour exposure conditions.

Figure 10 shows the measured percent moisture weights at each of the storage times. The percent moisture weight continuously decreases during storage as would be expected. The interesting point to learn from this data is that one cannot use average moisture content to justify the maximum in reflow damage response that was observed at the six day storage time. The percent moisture remaining in the packages after six days of storage appears to be a very small amount, e.g., 0.0053% for the 16 hour exposure and 0.013% for the 48 hour exposure. The position of the moisture gradient within the package is what controls the ultimate reflow response and not the integrated quantity of moisture revealed by examining weight gain data alone.

High Temperature Baking

A bake experiment was carried out on a 100 pin BQFP package. The experimental flow is shown in Figure 11. Packages were initially baked for 72 hours @ 125°C to remove all moisture. Devices were then subjected to either 71 hours or 168 hours at 30°C/60%RH. At this point, groups of devices were again baked at 125°C for times ranging from 4 to 48 hours. After baking, the devices were convection oven reflowed to a package body temperature of 220°C followed by C-SAM inspection.

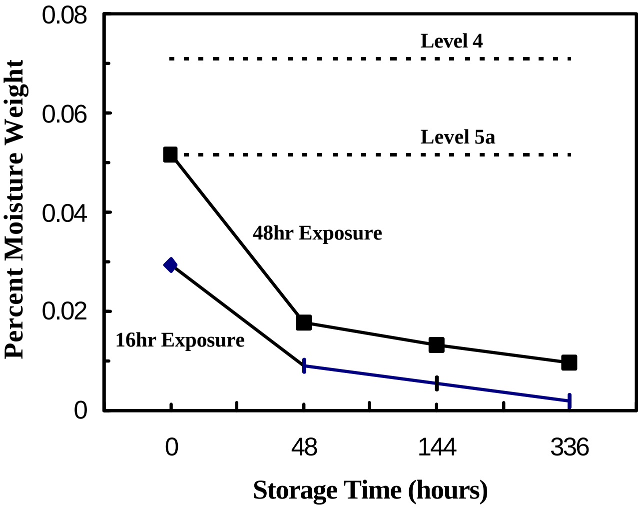

Fig. 10 Measured percent moisture content during storage.

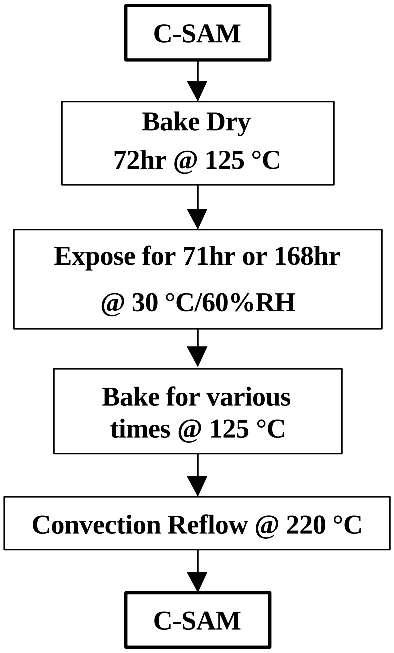

Fig. 11. Experimental flow for exposure/bake experiment.

Figure 12 shows the die surface delamination response observed. Plotted is the percentage of packages with greater than 5 area percent die surface delaminations for both the 71 hour and 168 hour exposures. A bake of 24 hours for the 71 hour exposed devices was found to produce a minimum delamination response. For the 168 hour exposed devices, a bake of 48 hours was required for a minimum delamination

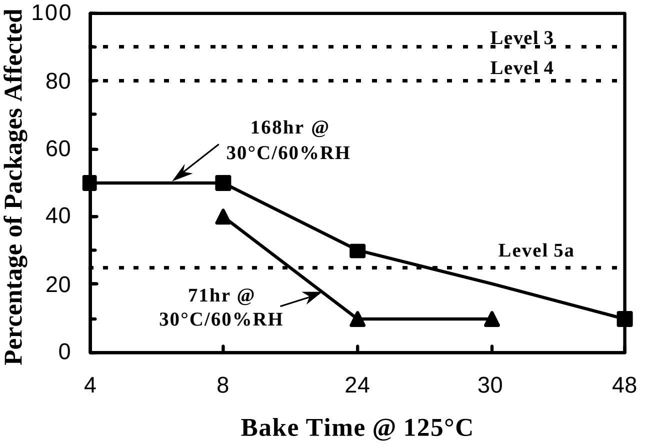

Fig.12. Percentage of packages with die surface delaminations greater than 5% by area for exposure/bake experiment.

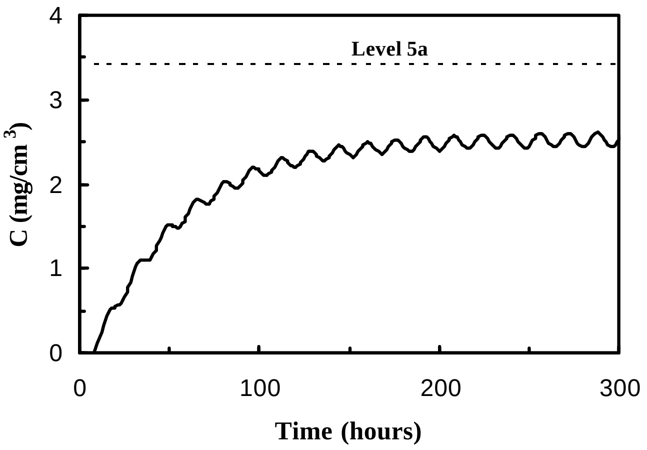

Fig. 13. Interface response for a TQFP package if exposed to a periodic condition of 8 hours at 25°C/60%RH plus 8 hours of drying at 25°C/0%RH.

response. Calculations for the 71 hour exposed devices show 22 hours of baking are needed to lower the interface concentration below the concentration achieved during the Level 5a test. For the 168 hour exposure, a bake time of 26 hours is required. The observed delamination responses tend to support these calculated times.

Discussion

Interface moisture concentration plays a vital role in the delamination response during high temperature solder reflow. Floor-life performance for highly-moisture sensitive devices will be ambient exposure path dependent while low humidity storage is considered effective only when perturbations of moisture exposure are initially short in duration. Safe moisture/reflow performance may not be achieved if initial exposure times prior to storage exceed more than a few hours. Safe exposures times will be dependent on several factors such as the mold compound thickness, the moisture diffusivity, the ambient exposure conditions, and effectively the rated moisture level of the package.

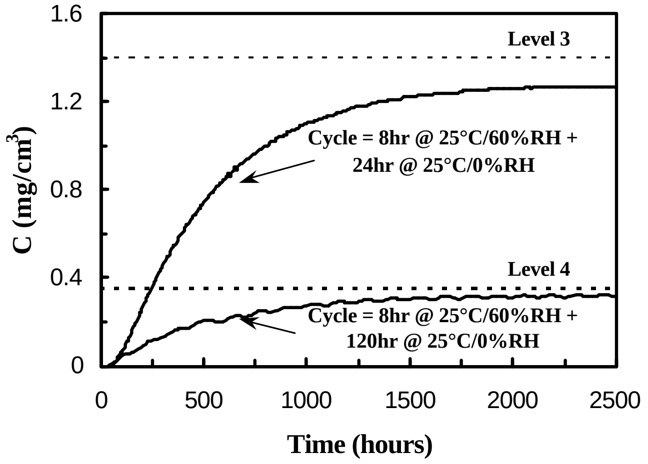

Fig. 14. Interface response for a PLCC package when subjected to a cyclic exposure.

Floor-life extension may be achievable for certain devices by cyclic ambient exposure followed by dry containment. This procedure has been discussed as a viable approach in previous work [7]. Here the interface concentration is prevented from exceeding $C_{critial}$ and achieves an asymptotic oscillation below $C_{critial}$. Figure 13 highlights this effect for a thin TQFP package having a mold compound diffusivity that follows equation (7). This approach becomes more difficult to achieve in a reasonable time for thicker devices such as PLCCs as shown in Figure 14. A cyclic exposure of 8 hours at 25°C/60%RH requires a dry containment of 24 hours to maintain an asymptotic maximum below the Level 3 $C_{critial}$ interface concentration. For a Level-4 PLCC package, the required dry containment time increases to 120 hours which is considered much too long for a manufacturable process.

Conclusions

Moisture diffusion is a thermodynamic temperature activated process that does not stop by simply placing a device in dry storage. Perturbations of moisture exposure followed by dry storage will allow moisture to reach critical internal interfaces which can result in an increased risk for moisture/reflow induced damage. The best procedure for handling moisture sensitive devices is to assemble them within the recommended JEDEC floor-life times. If this cannot be accomplished, then dry containment storage is a viable option provided the duration of initial ambient exposure is less than eight hours. For exposures longer than eight hours, diffusion kinetics will need to be considered. Cyclic storage can be used as an option to extend the floor-life, however, its usefulness as a manufacturable process is essentially limited to thin packages. High temperature baking to remove excess moisture will have similar concerns if the bake times are not long enough. Bake times can be optimized only if prior moisture exposure conditions are adequately known.

Acknowledgements

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