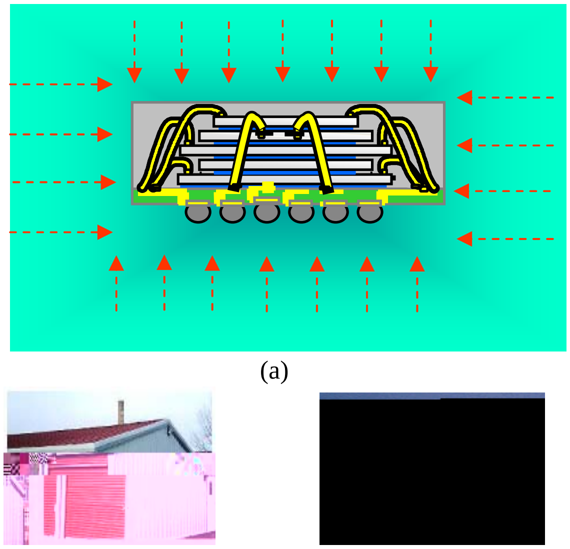
Daniel Shi[1], Xuejun Fan[2,3], Bin Xie[1]
[1]Hong Kong Applied Science & Technology Research Institute, Hong Kong Science Park, Shatin, Hong Kong, PRC
Email: danielshi@astri.org
[2]Department of Mechanical Engineering, Lamar University, PO Box 10028, Beaumont, TX 77710, USA
Email: xuejun.fan@lamar.edu
[3]Department of Engineering Mechanics, South China University of Technology, Guangzhou 510640, People's Republic of China

In order to devise an equivalent accelerated moisture sensitivity test, the JEDEC specification J-STD-020C has recommended an accelerated preconditioning time of 40hrs exposure under 60°C/60%RH, which is considered equivalent to the standard moisture sensitivity level 3 (MSL-3) of 216hrs soak time under 30°C/60%RH. However, the existing methodology for the accelerated moisture sensitivity test was developed based on the equivalency of local moisture concentration at the interest of location for leaded packages only. The failure mechanism is restricted to the potential delamination between mold compound and leadframe. In addition, such an equivalency requires the activation energy of molding compound for moisture diffusion in the range of 0.4 - 0.48eV. This paper introduces a new method to accelerate JEDEC/IPC moisture sensitivity level testing. The methodology is developed based on the equivalency of *both* local moisture concentration and overall moisture distribution of packages. The local moisture concentration equivalency ensures identical adhesion strength and vapor pressure at interfaces of the interest, and the overall moisture distribution equivalency results in the same condition of applied driving forces, such as thermal and hygroscopic stresses, during reflow. In our previous study [1], this methodology was applied to a molded matrix array package, and an accelerated soak time subjected to 60°C/60%RH was established. In this paper, the further reduction of soak time using 85°C/60%RH is investigated. An ultra-thin stacked-die chip scale package (CSP) is used as the test vehicle. Extensive experiments have been carried out to obtain the failure rate as function of soak time under various environmental conditions. Finite element analysis was performed to obtain the equivalency conditions. According to finite element modeling results, it has been found that, at 70hrs under 60°C/60%RH and 45hrs under 85°C/60%RH, respectively, both the local moisture concentration at critical interface and overall moisture distribution of package become identical to that under the standard MSL-3. Such an equivalency of the new accelerated test conditions has been proven by the test results. Failure site and failure mode indicates that the proposed accelerated tests are well correlated with the standard MSL-3. The new methodology can be extended to other packages.

Cracking and delamination subjected to moisture is one of key failure modes for plastic electronics packages at soldering reflow. The failure mechanism is due to the combined effects of thermo-mechanical stresses, hygroscopic stresses, vapor pressure, material softening, and adhesion degradation. For ultra-thin chip scale packages (CSP) in telecommunications, moisture absorption in a package reaches saturation level before the required soak time due to the thin feature of such a thermal stresses due to thermal mismatch and hygrostresses due to hygroscopic swelling mismatch.

This paper introduces a new methodology of the accelerated JEDEC/IPC moisture sensitivity level test. The methodology is developed based on the equivalency of both local moisture concentration (i.e., equivalency of vapor pressure) and overall moisture distribution (i.e., equivalency of thermal stresses and hygrostresses) of packages. Finite element analysis (FEA) is applied for moisture diffusion and vapor pressure analysis under various environmental conditions to determine the equivalent soak times. The equivalency of the new test conditions is proven by moisture/reflow experiments under various soak times.

The JEDEC/IPC moisture sensitivity/reflow test consists of two stages. Stage I is the process of moisture soaking, in which a specific combination between ambient temperature, relative humidity and soak time is defined to mimic factory environment during storage before surface mounting, as shown in Fig. 1.



(a)

(b)

Fig. 1: (a) Moisture soak in the stage I of JEDEC/IPC moisture sensitivity test, (b) moisture soak of plastic packages during storage and shipping

Stage II is the process of rapid heating to simulate the surface mounting soldering reflow process, as shown in Fig. 2. The entire packages with lead-free materials are exposed to an elevated temperature environment with peak temperature as high as 260°C or even 270°C.

During surface mounting, thermal stresses are developed due to thermal mismatch. [5-7]. The thermal strain, ε_T, at the soak temperature can be expressed as

$$_{T} = \quad T \qquad (1)$$

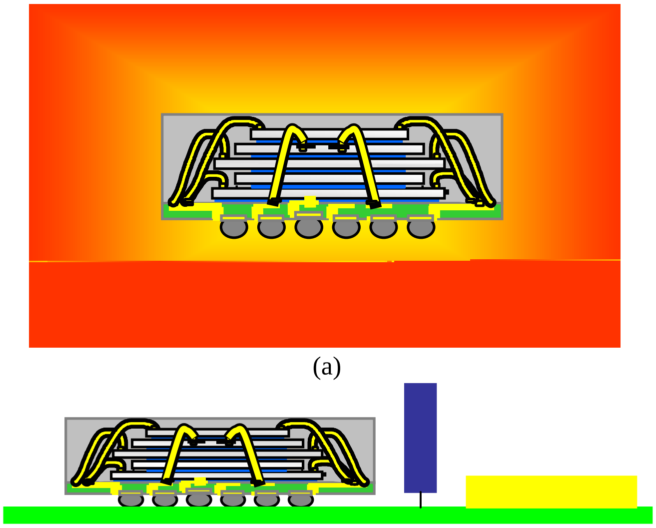
where is the coefficient of thermal expansion (CTE), and T is the temperature change. Similarly, hygroscopic stresses are developed due to hygroscopic swelling mismatch [8-12]. The hygroscopic swelling strain, ε_H, at the soaking humidity condition can be expressed as

$$_{H} = \quad C \qquad (2)$$

where is the coefficient of hygroscopic swelling , and C is the moisture concentration. During the soak, the moisture condenses in the micropores or free volumes of porous materials. The moisture vaporization generates high vapor pressure [13-17]. Generally, the driving forces inducing failures are thermal stress, hygro-stress and vapor pressure in the moisture sensitivity level test, which can be described as

$$= \ _{T} + \ _{H} + P \qquad (3)$$

where is total driving forces inducing failures, p is the vapor pressure.



(a)

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Fig. 2: (a) Rapid heating in the stage II of JEDEC/IPC moisture sensitivity test, (b) surface mounting soldering reflow process

The existing methodology for accelerated moisture sensitivity test was developed based on the equivalency of local moisture concentration at the critical interface. Local moisture concentration determines local vapor pressure and interfacial adhesion. The equivalency of local moisture concentration can ensure the equivalency of local vapor pressure and interfacial adhesion theoretically. However, the equivalency of local moisture concentration is not enough to ensure the equivalency of local thermal stress and hygro-stress, because the local thermal stress and hygro-stress are affected by the overall temperature and moisture distributions of the whole electronic package. Therefore, to ensure the equivalency of all driving forces (i.e., thermal stress, hygro-stress and vapor pressure) between the standard and accelerated moisture sensitivity level tests, not only the local moisture concentration at the critical interface but also the overall temperature and moisture distributions of the whole electronic package should be equivalent to achieve the equivalency of failure mode and failure rate.

This paper introduces a new methodology that can accelerate the IPC/JEDEC moisture sensitivity level test of an ultra-thin stacked-die CSP. The methodology is mainly developed based on the equivalency of both local moisture concentration and the overall moisture distribution. The local moisture concentration equivalency would be established first to ensure the equivalency of vapor pressure. Further, in order to ensure the equivalency of hygro-stress within different soak conditions, the overall moisture distribution would be indistinguishable. If the level of total driving forces is below the level of interface adhesion strength, the failure of cracking/delamination would not occur. Otherwise, the failure would occur. If the start points of cracking/delamination occurrence of standard and accelerated tests are in the same level, the failure rates between two tests are treated as equivalency, as shown in Fig. 3.

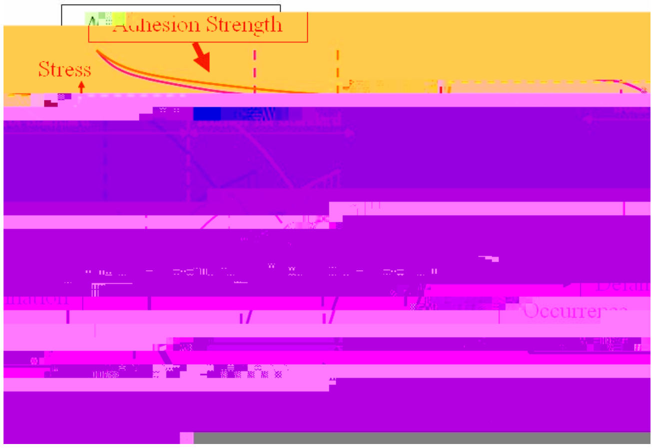


Fig. 3: Methodology of new moisture accelerated test

To implement the new methodology, a novel direct concentration approach (DCA) was developed and applied in this study to determine the equivalency of local moisture concentration as well as the overall moisture distribution under 30^{o}C/60%RH, 60^{o}C/60%RH and 85^{o}C/60%RH, respectively. The approach can simulate the moisture diffusion of the package under both constant and varying ambient temperature and humidity conditions [18,19]. In the approach, the moisture concentration is used as the field variable directly and constraint equation is used to ensure the interfacial continuous condition. To validate the new methodology and modeling results, the moisture/reflow tests were performed under the conditions of MSL-3 and 30hrs-, 45hrs-, 60hrs-, 75hrs-, 88hrs-60^{o}C/60%RH and 30hrs-, 45hrs-, 60hrs-85^{o}C/60%RH, respectively. The sample size was 48 units for each condition. The experimental procedures used were: Firstly, the thru-scanning acoustic microscope (TSAM) was adopted for the initial inspection to ensure no cracking/delamination occurring before moisture/reflow test. All the packages were baked for 24hrs at 125^{o}C to remove the initial moisture inside. Secondly, the packages absorbed the moisture under the above conditions. After the moisture soak, the packages were subjected to 3 cycles of JEDEC standard reflow with the peak temperature of 260^{o}C. Lastly, the TSAM was used again for the final inspection to determine the failure rate. A 3D ultra-thin stacked-die CSP was employed as test vehicle for both numerical simulations and experimental validation, as shown in Fig. 4. It consists of molding compound (MC), silicon die, die-attach film, solder resist (SR) and bismaleimide-triazine (BT) core. In the previous study, most cracking/delamination failure of die-attach film was found in the bottom film. Therefore, the study of moisture distribution and driving forces inducing cracking/delamination focused on the bottom film in this paper.

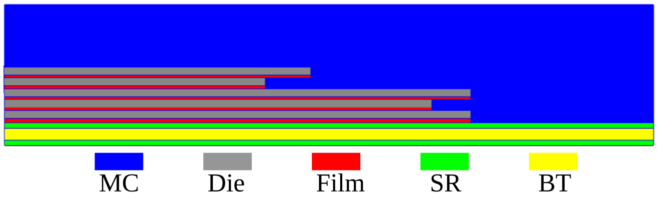


Fig. 4: The schematic structure of test vehicle

1. *Moisture Diffusion Modeling*

The moisture soak histories at the bottom film/substrate interface under 30^{o}C/60%RH, 60^{o}C/60%RH and 85^{o}C/60%RH are shown in Fig 5. The local moisture concentration at the interface is saturated after 100hrs under 30^{o}C/60%RH, 40hrs under 60^{o}C/60%RH and 25hrs under 85^{o}C/60%RH. It means from 40hrs under 60^{o}C/60%RH and 25hrs under 85^{o}C/60%RH, the local moisture concentration is equivalent with that under MSL-3. However, it does not mean 40hrs under 60^{o}C/60%RH and 25hrs under 85^{o}C/60%RH are equivalent with MSL-3.

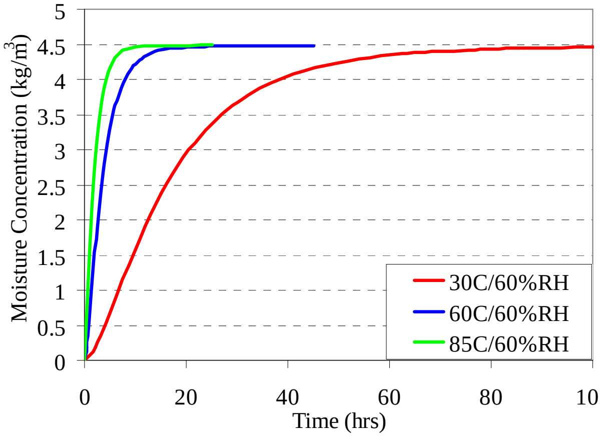
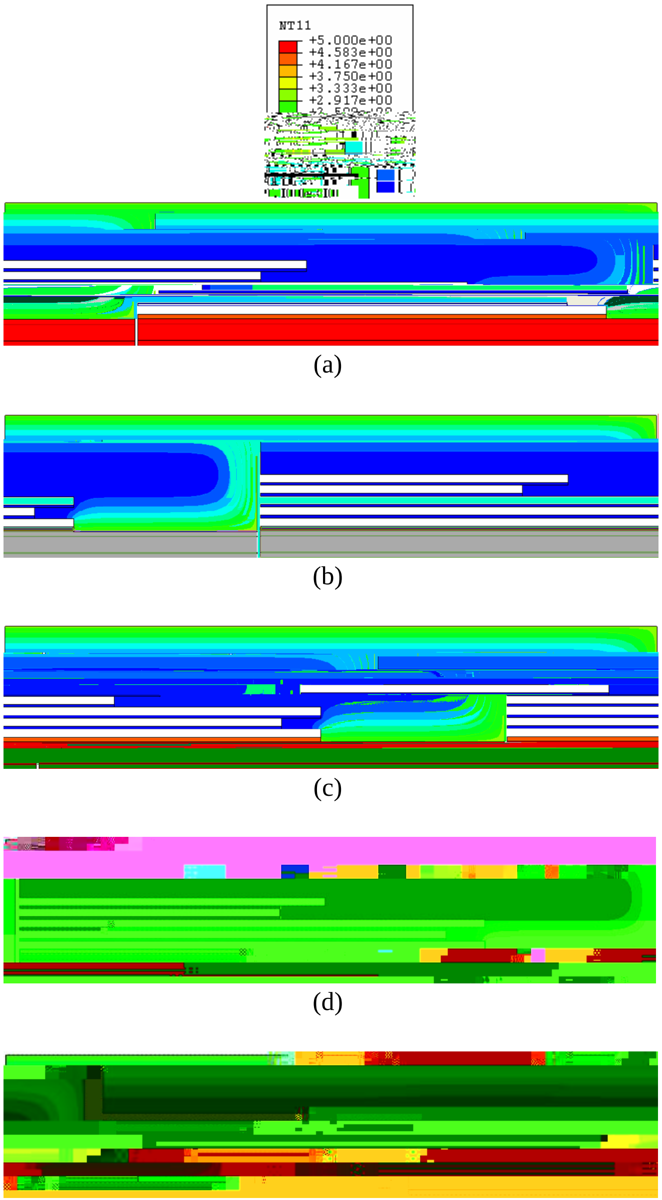


Fig. 5: Moisture soak histories under 30^{o}C/60%RH, 60^{o}C/60%RH and 85^{o}C/60%RH

To determine the equivalent soak times under 60^{o}C/60%RH and 85^{o}C/60%RH, the overall moisture distribution in the package would be investigated. FEA of moisture diffusion was performed for MSL-3 and 45hrs-, 70hrs-60^{o}C/60%RH and 25hrs-, 45hrs-85^{o}C/60%RH. The modeling results are shown in Fig. 6. Comparing Fig. 6(a) with Fig. 6(b), it is observed that although the local moisture concentration at bottom film reaches the same under 45hrs-60^{o}C/60%RH as that under MSL-3, the overall equivalency of moisture distribution is not reached yet at this time. Not only the local moisture concentration at the bottom film/substrate interface but also overall moisture distribution under 70hrs-60^{o}C/60%RH are equivalent with that of soak for MSL-3. Similarly, the overall equivalency of moisture distribution is not reached yet under MSL-3 and 25hrs-85^{o}C/60%RH, as shown in Fig. 6(a) and (d). Until soak for 45hrs-85^{o}C/60%RH, the overall moisture distribution is equivalent with that of soak for MSL-3, as shown in Fig. 6(e) and (a).



(a)

(b)

(c)

(d)

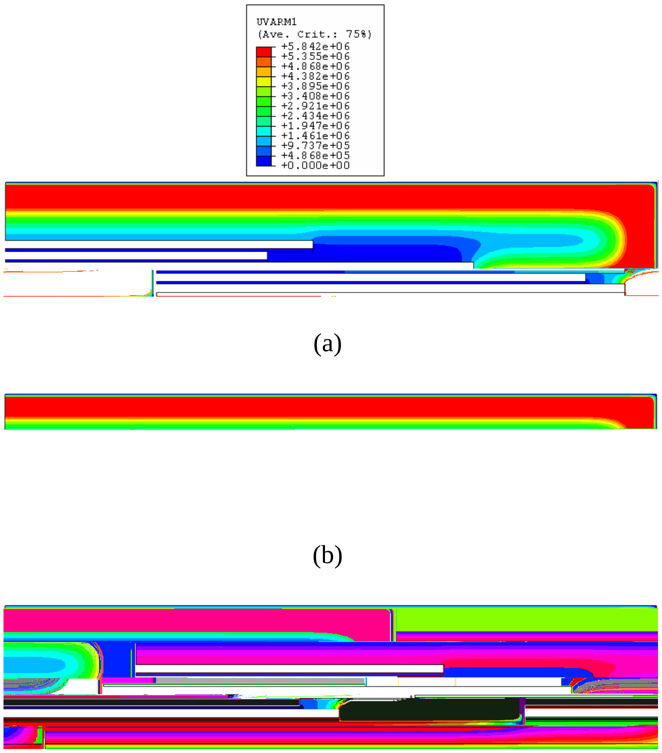
(e)

Fig. 6: Moisture distribution contours of soak under (a) MSL-3, (b) 45hrs-60^{o}C/60%RH, (c) 70hrs-60^{o}C/60%RH, (d) 25hrs-85^{o}C/60%RH and (e) 45hrs-85^{o}C/60%RH

Therefore, the moisture distribution at reflow temperature of 260^{o}C after soak under MSL-3, 70hrs-60^{o}C/60%RH and 45hrs-85^{o}C/60%RH would be equivalent due to the same reflow process, inducing the equivalent vapor pressure, thermal stress and hygro-stress under these three conditions at high reflow temperature. The equivalent driving forces for cracking/delamination could achieve the equivalent failure mode and failure rate after soak under MSL-3, 70hrs-60^{o}C/60%RH and 45hrs-85^{o}C/60%RH.

2. *Vapor Pressure Modeling*

To validate the equivalency of vapor pressure at the conditions of 70hrs-60^{o}C/60%RH and MSL-3 during the reflow process, the vapor pressure modeling was performed based on the simplified micromechanics vapor pressure model [18,19]. The simplified micromechanics vapor pressure model was developed with the user-defined subroutine based on the widely used micromechanics vapor pressure model [14-17]. Fig. 7 shows the contours of vapor pressure distribution under MSL-3 and 45hrs-, 70hrs-60^{o}C/60%RH at the reflow temperature of 260^{o}C. The vapor pressure is equivalent at the conditions of 70hrs-60^{o}C/60%RH and MSL-3. Also as indicated by the results of vapor pressure modeling under 85^{o}C/60%RH, the vapor pressure is also equivalent under 45hrs-85^{o}C/60%RH and MSL-3.



(a)

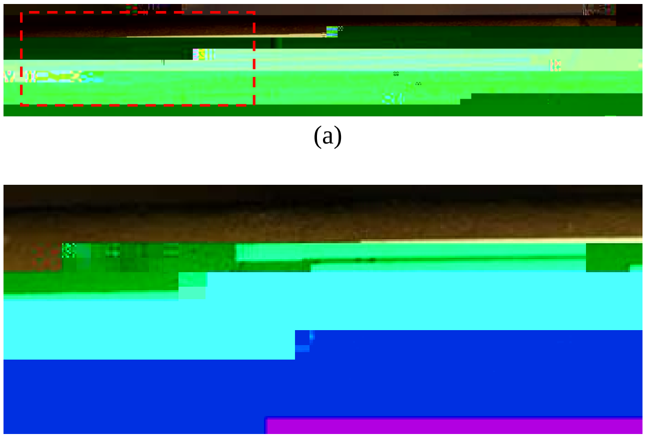
(b)

(c)

Fig. 7: Vapor pressure contours (at reflow temperature of 260^{o}C) of soak under (a) MSL-3 and (b) 45hrs-60^{o}C/60%RH, (c) 70hrs-60^{o}C/60%RH

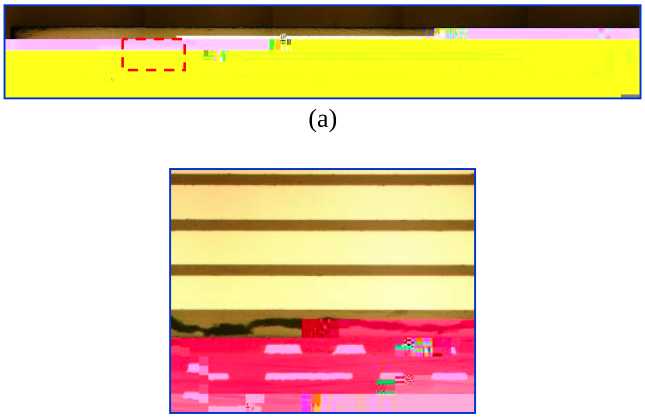
1. *Failure Mode/Location Identification*

In order to validate the failure mode/location of the package under MSL-3, 70hrs-60^{o}C/60%RH and 45hrs-85^{o}C/60%RH, the failure analyses were conducted on the failed samples. As shown in Figs. 8, 9 and 10, the cracking/delamination occurred inside the bottom film for these three conditions, i.e., cohesive delamination.


(a)

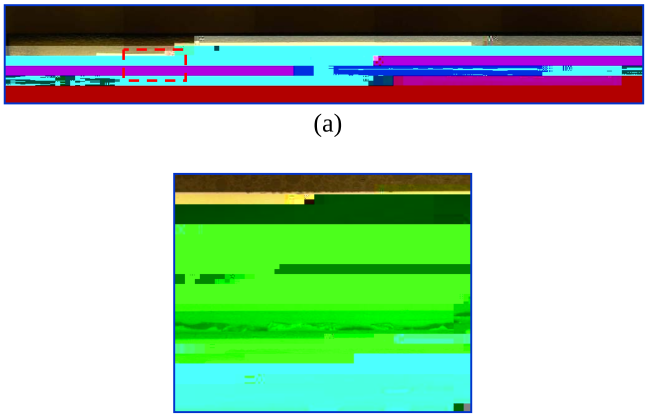
(b)

Fig. 8: (a) Cross-section view of the ultra-thin stacked-die CSP under MSL-3, (b) zoom-in view of highlighted region in (a)


(a)

(b)

Fig. 9: (a) Cross-section view of the ultra-thin stacked-die CSP under 70hrs-60°C/60%RH, (b) zoom-in view of highlighted region in (a)


(a)

(b)

Fig. 10: (a) Cross-section view of the ultra-thin stacked-die CSP under 45hrs-85°C/60%RH, (b) zoom-in view of highlighted region in (a)

2. *Determination of Equivalent Failure rate*

It is derived from the FEA that 70hrs-60°C/60%RH and 45hrs-85°C/60%RH are equivalent to the MSL-3. To validate the modeling results, the moisture/reflow tests were performed with the stacked-die CSP test vehicle under the conditions of MSL-3 and 30hrs-, 45hrs-, 60hrs-, 75hrs-, 88hrs-60°C/60%RH and 30hrs-, 45hrs-, 60hrs-85°C/60%RH. After the moisture/reflow tests, the TSAM was used for the final inspection to determine the failure rate. The failure rate is defined as

$$R = n_f / n_t \tag{4}$$

where R is the failure rate, n_f is the number of failed samples, and n_t is the number of total samples.

The failure rate under the condition of MSL-3 is 4.6%, as shown in Fig. 11. The failure rates under the conditions of 60°C/60%RH but different times are also plotted in Fig. 11, they can be curve-fitted as

$$\begin{aligned} &R = 0 \quad \text{if } t < 57.2 \\ &R = 10^{0.05(t-57.2)} \quad \text{if } t > 57.2 \end{aligned} \tag{5}$$

where t is the soak time. By equaling the failure rates under 30°C/60%RH and 60°C/60%RH, the soak time under 60°C/60%RH can be determined as 68.3hrs to be equivalency with MSL-3. Similarly, the failure rates under 85°C/60%RH but different times are plotted in Fig. 11, they can be curve-fitted as

$$\begin{aligned} &R = 0 \quad \text{if } t < 36 \\ &R = 10^{0.05(t-36)} \quad \text{if } t > 36 \end{aligned} \tag{6}$$

By equaling the failure rates under 30°C/60%RH and 85°C/60%RH, the soak time under 85°C/60%RH can be determined as 47hrs to be equivalency with MSL-3. The experimental moisture/reflow tests validated the new methodology and modeling analyses.

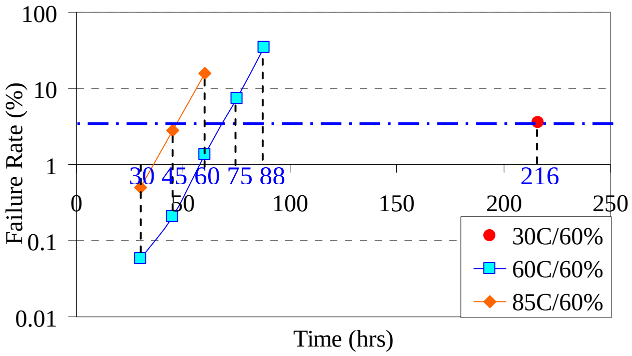


Fig. 11: Failure rates under 30°C/60%RH, 60°C/60%RH and 85°C/60%RH

With the analyses of modeling results and experimental validation, it is therefore concluded that the conditions of 70hrs-60°C/60%RH 45hrs-85°C/60%RH are equivalent with MSL-3 in terms of global moisture distribution and vapor pressure, local moisture distribution and vapor pressure, failure rate, failure location and failure mode.

This paper proposes a new methodology of accelerated moisture sensitivity test based on the equivalency of both local moisture concentration and overall moisture distribution. The new methodology can ensure the same failure mode/location and similar failure rate of cracking/delamination by the equivalency of local vapor pressure, interfacial adhesion as well as the thermal stress and hygro-stress. FEA modeling approaches were developed and applied for moisture diffusion and vapor pressure analysis of the package under various conditions of 30°C/60%RH, 60°C/60%RH and 85°C/60%RH. At 70hrs under 60°C/60%RH and 45hrs under 85°C/60%RH, both the local moisture concentration at critical interface and overall moisture distribution of package become identical with that under MSL-3, indicating that 70hrs-60°C/60%RH and 45hrs-85°C/60%RH is the equivalent soak time compared to MSL-3. Such equivalencies of the test conditions are proven by the corresponding moisture/reflow sensitivity experiments and the failure analyses, indicating that the accelerated tests correlated well with the MSL-3 test. The methodology developed in this work can be extended to other packages.

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