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USING FINITE ELEMENT ANALYSIS IN UNDERSTANDING PACKAGE MOISTURE ABSORPTION BEHAVIOR

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ABSTRACT

The presence of moisture in IC (integrated circuit) packages affects reliability. Moisture-induced failures like interface delamination are commonly encountered in the microelectronic packaging industry that uses epoxy molding compound as encapsulant or any moisture-permeable material. So a reliability test is usually done based on JEDEC standard to qualify an IC package at a certain moisture sensitivity level (MSL).

Therefore, understanding the moisture absorption behavior of a package is very important in order to properly address moisture-related package concerns. There needs to be some methodology to predict package moisture absorption even before an actual prototype could be manufactured and subjected to MSL tests. This paper uses 3D Finite Element Analysis (FEA) to analyze QFN (Quad Flat No-Lead) package moisture absorption, which is also compared to actual MSL test data. Results show that moisture absorption simulation done with ANSYS software's thermal-moisture analogy can be successfully used to analyze IC package moisture behavior.

1.0 INTRODUCTION

QFN (Quad Flat No-Lead) package has been in the microelectronic industry for quite some time and until now it is still a very popular low-cost solution for small package applications with low pin-count requirements.

However, a significant problem in IC packaging that also affects QFN packages is the presence of moisture-induced failures. Moisture introduces corrosion, development of hygro-stresses, popcorn failure, and deterioration of polymer interfaces that accelerates delamination [7]. Since moisture affects package reliability, there needs to be some methodology to understand and predict moisture absorption behavior of plastic encapsulated packages in order to develop more robust devices.

This paper uses 3D Finite Element Analysis to analyze QFN package moisture diffusion with the thermal-moisture analogy approach in ANSYS FEA software. This study includes analysis of moisture concentration distribution after moisture soak as well as the amount of moisture absorbed (percent moisture). Actual MSL data are also compared with the results of FEA simulation.

1.1 The QFN Package

The IC package used in this study is a QFN (Quad Flat No-Lead) type of package that has the following main components: (1) leadframe, which includes the copper leads & die pad , (2) die attach, which could be in form of glue or DAF (die attach film), (3) die, and (4) epoxy molding compound (EMC). Figure 1 shows a schematic of the QFN package.

The exposed peripheral leads are intended for soldering to the PCB (printed circuit board) as well as the center die pad that helps improve board level solder joint reliability and provides a heat transfer path to dissipate heat from the silicon die.

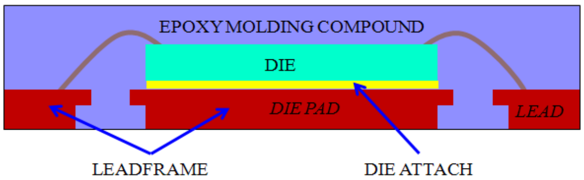

Figure 1. Schematic of the QFN Package

1.2 Moisture Sensitivity Levels (MSL)

JEDEC [5] has defined standard moisture soak requirements for moisture sensitivity testing as shown in Table 1. There are three common moisture sensitivity levels (MSLs) at which most electronic packages are tested: MSL 1, 2 and 3.

Table 1. Moisture Sensitivity Levels [5]

Level	Floor Life		Standard Soak Requirements	
	Time	Condition	Time (hours)	Condition
1	Unlimited	≤30°C/ 85% RH	168 +5/-0	85°C/ 85% RH
2	1 year	≤30°C/ 60% RH	168 +5/-0	85°C/ 60% RH
3	168 hours	≤30°C/ 60% RH	192 +5/-0	30°C/ 60% RH

For QFN devices, usually the package must pass at least MSL 3 (Level 3). It means that the package has been soaked for a total of 192 hours at 30°C/ 60% RH and shows no reliability issues like package crack or delamination after being subjected to 3 cycles of appropriate reflow condition, which is 260°C convection reflow temperature for lead-free packages.

2. 0 REVIEW OF RELATED LITERATURE

2.1 Moisture Diffusion

In quantifying transient or non-steady state moisture diffusion [1,2], the governing equation is described by Fick's second law as:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

where *C* is the moisture concentration and x, y, z are the spatial coordinates, *D* is the diffusion coefficient and *t* is the time.

Since the moisture concentration is not continuous at the interface of different materials, a wetness approach is generally used as:

$$w = \frac{C}{C_{sat}}$$

where *Csat* is the saturated moisture concentration and *w* is the wetness fraction. So, *w* = 0 means dry and *w* = 1 means fully wet. Then Fick's second law could now be transformed into:

$$\frac{\partial w}{\partial t} = \alpha_m\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right)$$

where α_m = *D*Csat*, or the product of the diffusion coefficient and the saturated moisture concentration.

2.2 Thermal-Moisture Analogy

When analyzing moisture diffusion problem, a thermal-moisture analogy is commonly used [1,3,4]. As we can see, Fick's second law is very similar to Fourier's mathematical expression for heat conduction. So this means that a diffusion problem can be analyzed using a typical heat transfer analysis in any finite element analysis (FEA) software. Table 2 describes the FEA thermal-moisture analogy.

Table 2. FEA Thermal-Moisture Analogy [3,4]

Properties	**Thermal**	**Moisture**
Field Variable	Temperature, T	Wetness, w
Density	ρ (kg/m^3)	1
Conductivity	k (W/m-C)	D*Csat (mg/s-mm)
Specific Heat	Cp	Csat (mg/mm^3)
CTE	α	β*Csat

3.0 EXPERIMENTAL SECTION

3.1 Moisture Sensitivity Level (MSL) Assessment

In the MSL assessment, a general MSL test flow was followed. An X-ray photo of the leadframe design was first taken to confirm construction. Then a SCAT was performed on "as-received" parts to check for any package issue. Prior to getting the dry weight, the parts were baked for 24 hours at 125°C.

After baking and weighing, the parts were then subjected to moisture soak or preconditioning per MSL test levels: 168 hours at 85°C/ 85% RH for parts to be tested at Level 1, 168 hours at 85°C/ 60% RH (Level 2) and 192 hours at 30°C/ 60% RH (Level 3). Then the parts were weighed again after moisture soak to get the percent moisture. A convection reflow at 260°C followed based on JEDEC reflow profile for lead-free packages.

When the convection reflow was completed, the packages were subjected to external visual inspection and SCAT. A cross section inspection was also conducted after SCAT inspection to confirm package crack or delamination issues.

Table 3. Package MSL Test Matrix

Package	Materials	Pkg. Size	Die Size	Pad Size
Package 1	EMC 1 [a] with DAF	5x5x0.85 mm	3.51x2.13 x 0.28mm	3.65x 3.65mm
Package 2	EMC 2 [b] with glue	5x5x0.85 mm	3.51x2.13 x 0.28mm	3.65x 3.65mm

[a] Epoxy Molding Compound 1
[b] Epoxy Molding Compound 2

3.2 Moisture Absorption Simulation

ANSYS FEA software was used in the moisture diffusion analysis. The first part of the simulation was verifying the thermal-moisture analogy technique on a bulk epoxy molding compound sample. A simple FEA quarter model as shown in Figure 2 was created for the 50x9.5x2 mm sample used to characterize the sample's moisture properties under 85°C/85% RH condition: D = 3.09e-6 mm^2/s and $Csat$ = 3.40e-3 mg/mm^3.

So basically, a transient thermal analysis was conducted and a temperature equal to 1 (wetness $w = 1$) was applied to the outer surface of the model to simulate moisture soak condition. The initial temperature was equal to 0 to simulate initially "dry" or baked sample (wetness $w = 0$).

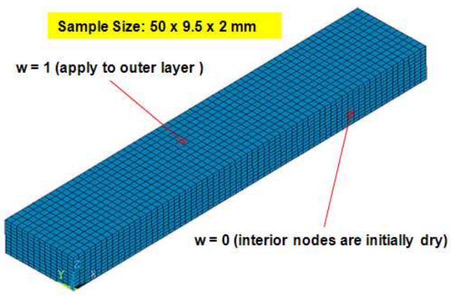

Figure 2. FEA Quarter Model of Mold Compound Sample

After the thermal-analogy technique implemented in ANSYS was verified, QFN package moisture absorption was then conducted. Figure 3 shows the FEA quarter model of the QFN package. The same boundary conditions applied on the bulk molding compound model were also used.

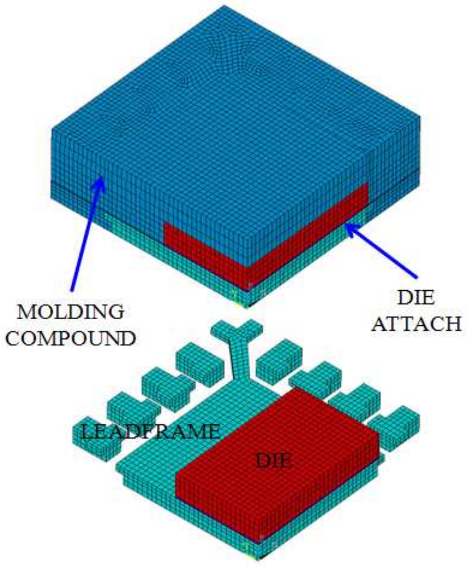

Figure 3. FEA Quarter Model of the QFN Package

Since the copper leadframe and the silicon die are considered impermeable, their diffusivity coefficient *D* and *Csat* are both equal to zero. But ANSYS software requires non-zero values to have non-singular stiffness matrix. So a very small value close to zero was used instead for the required moisture properties.

The rest of the moisture properties used in the package moisture diffusion analysis are listed in Tables 4 and 5. Since there is no internal data for the die attach materials, the moisture properties used for the glue and the die attach film (DAF) were assumed from published data[1]. And the *Csat* under MSL 2 condition is calculated as (60/85) x (*Csat* under MSL 1) by assuming that Henry's law applies: saturated moisture concentration is linearly proportional to the relative humidity [8].

Table 4. Moisture Material Properties (under MSL3 Condition or 30°C/ 60% RH)

Material	*D* (mm^2/s)	*Csat* (mg/mm^3)	β, CME [c] (mm^3/mg)
EMC 1	2.41e-7	1.83e-3	0.46
EMC 2	1.69e-7	2.54e-3	0.35
Glue [1]	1.25e-5	3.20e-3	0.52
DAF [1]	1.25e-5	3.20e-3	0.52

[c] coefficient of moisture expansion

Table 5. Moisture Material Properties (under MSL1 Condition or 85°C/ 85% RH)

Material	*D* (mm^2/s)	*Csat* (mg/mm^3)	β, CME (mm^3/mg)
EMC 1	1.59e-6	3.62e-3	0.46
EMC 2	1.22e-6	5.00e-3	0.35
Glue [1]	1.25e-5	3.20e-3	0.52
DAF [1]	1.25e-5	3.20e-3	0.52

4.0 RESULTS AND DISCUSSION

Table 6 shows the summary of MSL test results. Package 1, which uses EMC 1 and DAF, failed at MSL 1, 2 and 3 due to delamination which was worst at Level 1 where external package crack was also observed. The cross section and SCAT results for package 1 are shown in Figures 4 and 5.

Package 2, which uses EMC 2 and glue die attach, passed at MSL 2 and 3 but failed at MSL 1. This indicates that package 2 has better performance than package 1 even though its moisture absorption (percent moisture) is higher than that of package 1. Cross section in Figure 6 reveals no delamination of package 2 at MSL 2. Delamination was only encountered at MSL 1 where the moisture absorption is at its highest for package 2.

Table 6. Package MSL Test Results Summary

Package	MSL1	MSL2	MSL3
Package 1	FAILED (0.091% moisture; with delam & external crack)	FAILED (0.052% moisture; with delam & external crack)	FAILED (0.034% moisture; with delam)
Package 2	FAILED (0.120% moisture; with delam)	PASSED (0.075% moisture)	PASSED (0.061% moisture)

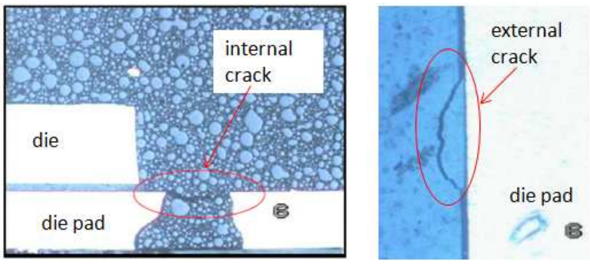

Figure 4. Cross Section of Package 1 revealing crack after MSL1

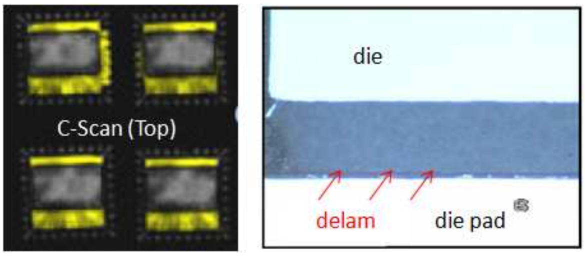

Figure 5. SCAT Photo and Cross Section of Package 1 (representative photo after MSL 1, 2 and 3)

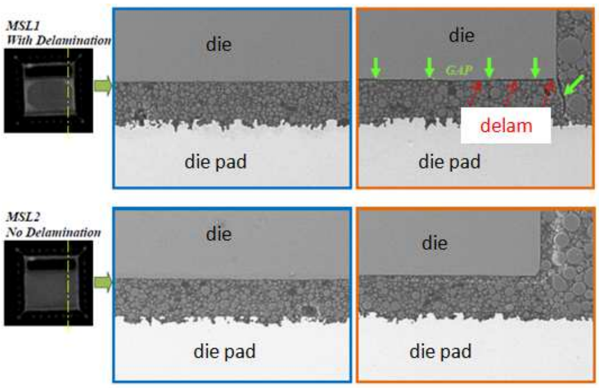

Figure 6. SCAT and Cross Section of Package 2

The result of the moisture diffusion simulation to verify the thermal-moisture analogy technique in ANSYS shows good correlation with the actual moisture data. The comparison between FEA simulation result and actual data is shown in Figure 7.

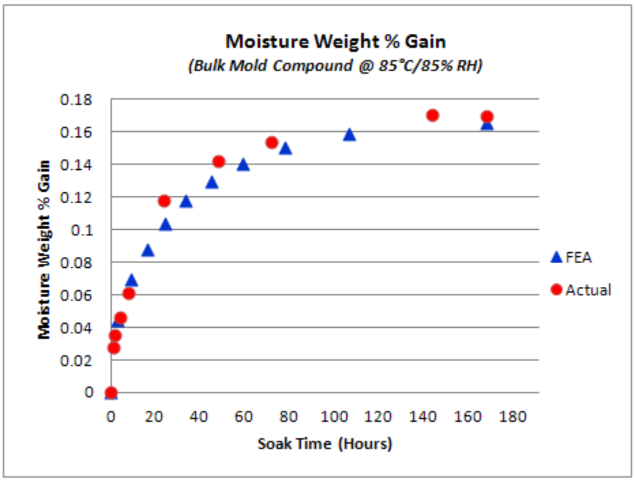

Figure 7. Moisture Weight Percent Gain of the Bulk Molding Compound (FEA vs Experiment)

Figure 8 shows the wetness distribution of the bulk molding compound after 168 hours of moisture soak and in Figure 9 is the equivalent moisture concentration distribution. The concentration contour plot is based on the calculation from the wetness results using the relationship: C = *w*Csat*.

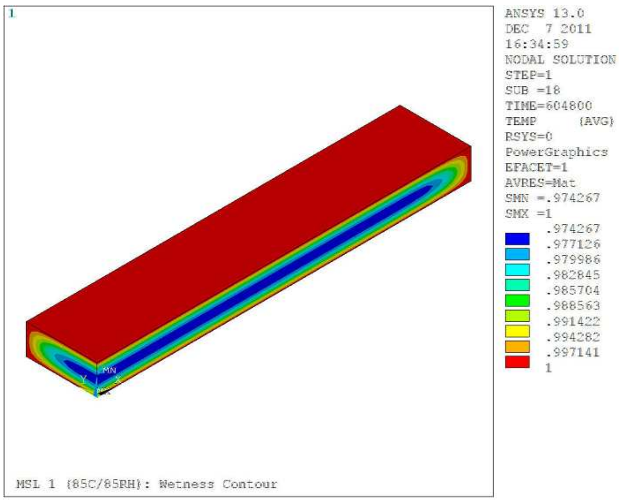

Figure 8. Moisture Wetness Distribution of the Bulk Molding Compound

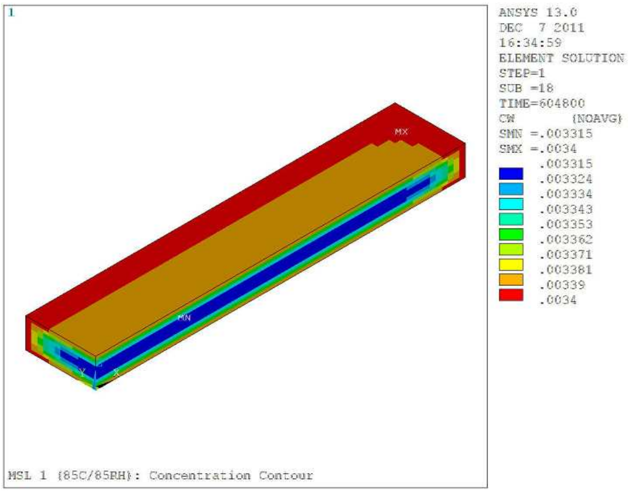

Figure 9. Moisture Concentration Distribution of the Bulk Molding Compound

The QFN package moisture wetness distribution and the corresponding concentration distribution predicted by FEA simulation are shown in Figures 10 and 11. The contour plots are for package 1 after being subjected to MSL 3 condition (192 hours at 30°C/ 60% RH). It can be seen in Figure 10 that there are still regions where the moisture concentration has not yet reached its saturation value (*Csat*). It can also be observed in Figure 11 that the die attach film (DAF) moisture concentration is higher on the side nearer to the die pad edge, which means that it can get weakened by the absorbed moisture earlier than the other side farther from die pad edge where the moisture concentration is lower.

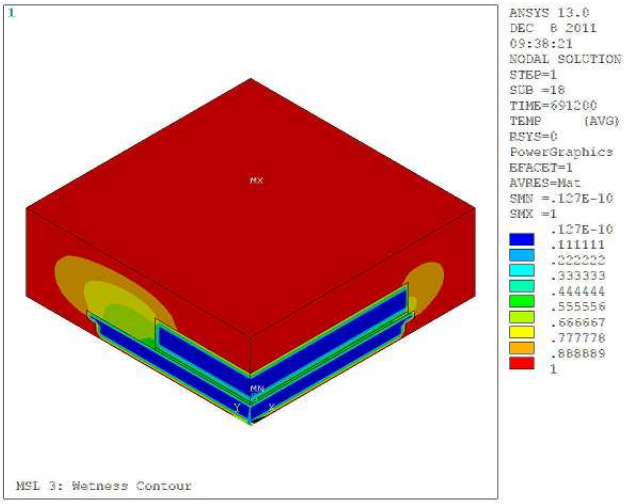

Figure 10. Package 1 Wetness Distribution (MSL 3)

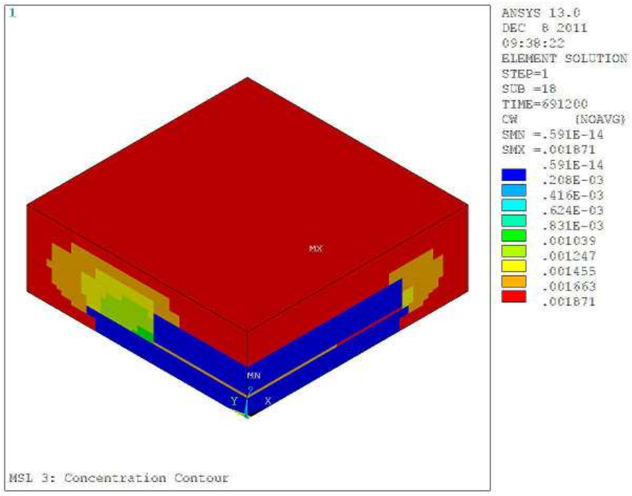

Figure 11. Package 1 Concentration Distribution (MSL 3)

Figures 12 and 13 show the comparison of percent moisture based on actual MSL test versus the percent moisture via FEA at different levels of MSL soak condition. And the graph of the data reveals a good agreement between the FEA predicted results and the actual moisture absorption at different moisture sensitivity levels especially at MSL 1 and MSL 3. At MSL 2 condition, the difference between FEA and actual results is a bit larger maybe because the moisture properties used were just calculated based on Henry's law application and not obtained by standard experiment. And the difference is somehow consistent between package 1 and package 2.

Among the 3 moisture sensitivity levels considered, the amount of moisture absorption is highest at level 1 and lowest at level 3. And this trend is successfully predicted by FEA simulation as shown.

For the same package, there is direct correlation between the amount of moisture absorption and the presence of package failures like delamination as demonstrated by package 2 that passed at MSL 3 (lowest percent moisture) but failed at MSL 1 (highest percent moisture). But for different packages used in this study (package 1 and package 2), no direct correlation exists between the amount of moisture absorption and the occurrence of failures. It is interesting to note that at MSL 3, package 1 has lower percent moisture than package 2 but it failed during actual MSL test and package 2 passed. It could be that package 2, which uses EMC 2 and glue die attach, has excellent resistance against interface strength degradation by the absorbed moisture.

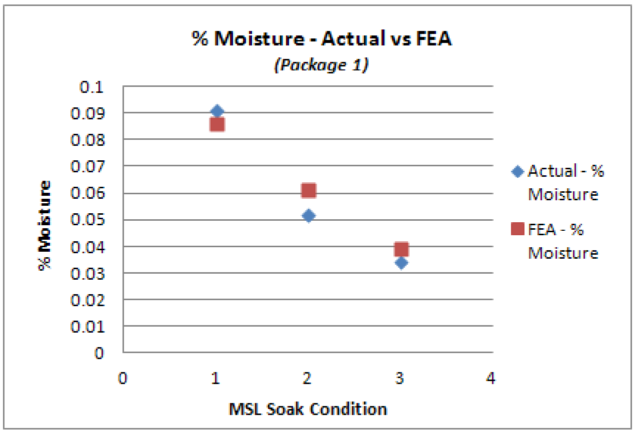

Figure 12. Package 1 - % Moisture (w/ EMC 1 & DAF)

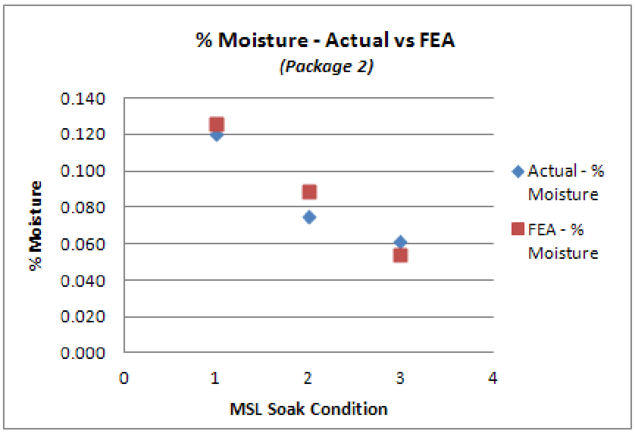

Figure 13. Package 2 - % Moisture (w/ EMC 2 & Glue)

5.0 CONCLUSION

In this study, it has been shown that moisture absorption FEA simulation done with ANSYS software's thermal-moisture analogy can be successfully used to analyze IC package moisture behavior. Based on the comparison, the actual moisture absorption data concur with the results via FEA simulation. This demonstrates the feasibility of using FEA to predict package moisture absorption in a much shorter time as compared to doing actual test and thus produce cost-effective and robust IC package designs.

The MSL results also reveal that for different QFN packages with different materials, moisture absorption (percent moisture) does not have direct correlation with the presence of package failures. A package may fail even with less moisture absorption if the adhesion of the interface (molding compound/leadframe or die/glue/leadframe) is easily weakened by the absorbed moisture. But for the same package (materials and configuration), direct correlation exists between the amount of moisture absorption and the occurrence of package failures.

6.0 RECOMMENDATIONS

Based on the results, it is recommended that Finite Element Analysis (FEA) be used in analyzing package moisture absorption of electronic packages.

Since moisture affects adhesion strength of QFN package interface (leadframe/epoxy molding compound and leadframe/die attach or die/die attach), it is also recommended that actual adhesion strength experiment be conducted.

Further studies on hygro-mechanical and thermo-mechanical stress analysis should be done so that a reliable package FEA model could be used to quickly do a virtual MSL testing even before an actual prototype is being fabricated.

7.0 ACKNOWLEDGMENT

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