Study on the Board-level SMT Assembly and Solder Joint Reliability of Different QFN Packages

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Abstract

The current paper deals with firstly the optimized SMT to assemble various types of QFN (Quad Flat Non-leaded) packages. The important SMT factors such as solder pad and stencil designs will be discussed. Secondly and more importantly, this paper will detail the comprehensive experiment and simulation work done for QFN solder joint reliability modeling. A curve fitted fatigue correlation model together with the use of Schubert's hyperbolic sine lead-free solder constitutive model will be proposed for accurate QFN solder joint reliability prediction.

1. Introduction

The consumer and communication electronics industry demands for lighter, thinner and higher performance packages. QFN package is able to meet those requirements because of its superior thermal and electrical performance. QFN packages can effectively dissipate heat because the exposed pad decreases the thermal resistance. The exposed pad also helps improve electrical performance of QFN by minimizing package ground lead inductance.

Compared to a QFP (Quad Flat Package) package whose leads protrude from the package body, QFN's small body size and footprint are especially favorable in miniaturized electronic devices such as handheld and communication products. Although may meet all package-level reliability requirements, QFN still has board-level concerns. For example, the SMT (surface mount technology) assembly of QFN is one of the board-level challenges. Non-optimized process may lead to low yield of board-level assembly and poor solder joint reliability under temperature cycling on board (TCoB) test. Unlike QFP, whose compliant leads can absorb the strain caused by CTE (coefficient of thermal expansion) mismatch between the package and PCB, the leadless feature of QFN makes it have very rigid connection with the PCB. What's worse, the solder used to connect the package to PCB is solely from paste printing. This makes the solder joint height of QFN is very low, which is another concern under TCoB test.

QFN family includes many members that have different configurations to meet various needs in different applications. Figure 1 describes the schematic pictures of the various QFN packages under the current study. Figure 1-A is a punch-type VQFN which is molded in individual mold cavity. Figure 1-B and 1-C are saw-type VQFNs, which are molded in panel and sawed subsequently in singulation process. The difference between B and C is the lead pullback design. Figure 2 can better illustrate the difference between lead pullback and non-pullback designs. The advantages of using lead pullback design are reduction of lead smearing (which cause short of adjacent leads) and cutting blade wearout in package singulation process (due to the half-etch feature). However, as shown in Figure 3, lead pull back design prevents the solder from wetting the side surface of the exposed lead and thus causes poorer solder joint reliability as compared to lead non-pullback design and punch-type QFN.

HQFN and et-QFN, as shown in Figure 1-D and 1-E, are two QFN packages that are intended for applications requiring enhanced thermal performance. For HQFN, the dummy die attachment possibly increases the board-level solder joint reliability concern as silicon is well-known to be the major source of CTE mismatch. For et-QFN, the die pad is exposed at the package top instead of bottom. Compared with other QFN packages, the lacking of center pad soldering also makes board-level solder joint reliability a concern.

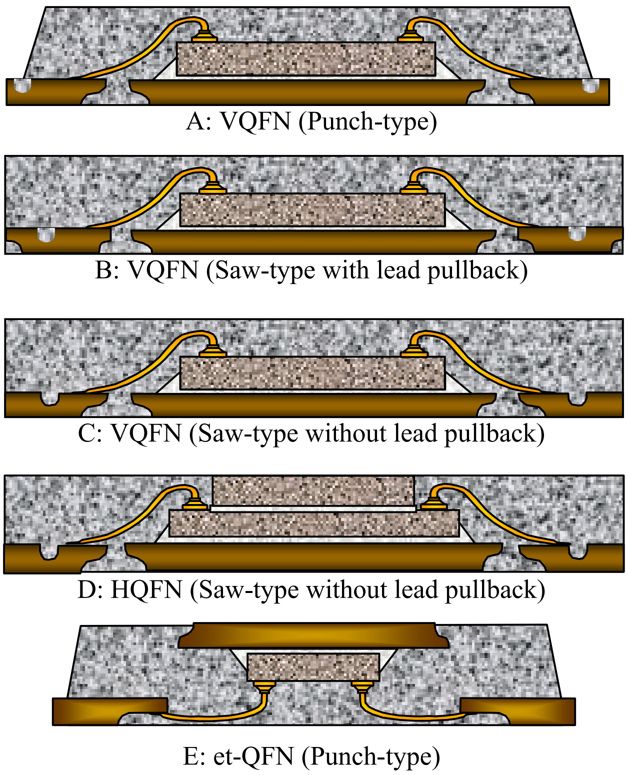


Figure 1: Various QFN package structures

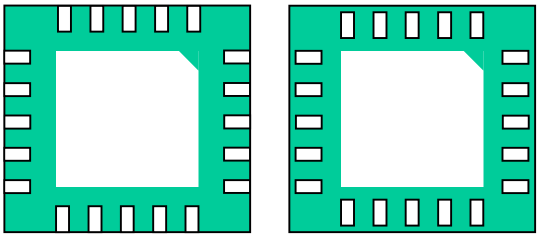
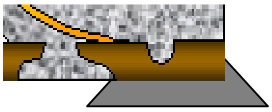
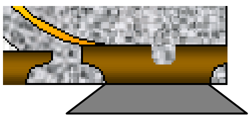


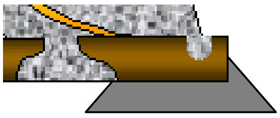
Figure 2: Bottom view of the difference between lead pullback and non-pullback
(left: non-pullback, right: pullback)



A: Solder joint of saw-type QFN (lead non-pullback)



B: Solder joint of saw-type QFN (lead pullback)



C: Solder joint of punch-type QFN
Figure 3: Solder joint formation for different QFNs

2. SMT assembly of QFN packages

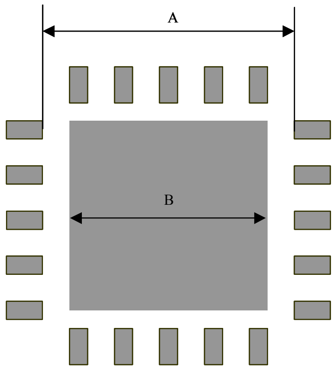
The matrix for current QFN board-level study is listed in Table 1. Some important parameters such as exposed peripheral lead size and center paddle size are given. It is known that the PCB pad design and the stencil design are most critical for successful and quality SMT assembly of QFN packages. Those important design considerations are discussed by Syed and Kang in [1], which is used as the SMT design reference in the current study.

The PCB pad design for all the legs in Table 1 are shown in Figure 4. The solder pad size corresponding to exposed peripheral leads is 0.9x0.3mm for all legs.

Some of the important stencil design parameters are depicted in Figure 5. The stencil used in current study is a 5mil stainless steel stencil by laser cutting. By using those SMT design parameters discussed here, all the QFN legs are assembled successfully with good solder joint fillet formation as is shown in Figure 10.

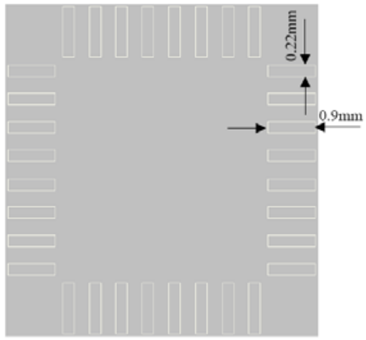
Table 1: QFN matrix under the current study

Leg#	Pkg Type	Size/Pitch (mm)	Exposed Lead Size	Die Paddle (exposed)	I/O	Solder
Leg 1	VQFN-P	5x5x0.90/0.50	0.40x0.25	3.500x3.500	32	SnPb
Leg 2	VQFN-P	5x5x0.90/0.50	0.40x0.25	3.500x3.500	32	Pb-free
Leg 3	et-QFN-P	5x5x0.90/0.50	0.40x0.25	1.920x2.900	32	SnPb
Leg 4	et-QFN-P	5x5x0.90/0.50	0.40x0.25	1.920x2.900	32	Pb-free
Leg 5	et-QFN-P	5x5x0.90/0.50	0.40x0.25	1.920x2.900	32	Pb-free
Leg 6	VQFN-P	6x6x0.90/0.50	0.40x0.25	4.10x4.10	40	Pb-free
Leg 7	VQFN-S	6x6x0.90/0.50	0.35x0.25	4.25x4.25	40	Pb-free
Leg 8	VQFN-S	8x8x0.90/0.50	0.40x0.25	5.900x5.900	56	Pb-free
Leg 9	HQFN-S	8x8x0.90/0.50	0.40x0.25	5.900x5.900	56	Pb-free

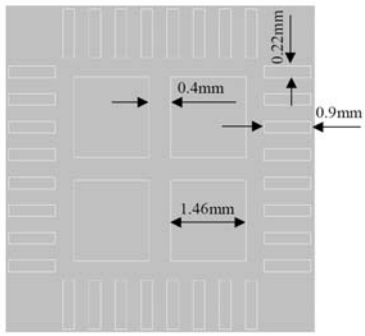


5x5mm et-QFN	A=4mm	B=N.A.
5x5mm VQFN	A=4mm	B=3.6x3.6mm
6x6mm VQFN	A=5mm	B=4.55x4.55mm
8x8mm VQFN/HQFN	A=7mm	B=6.2x6.2mm

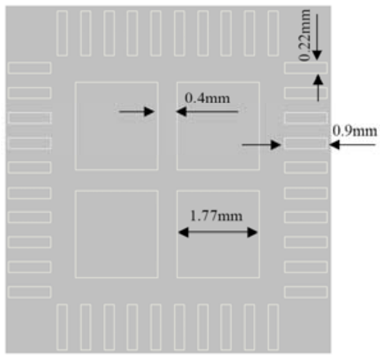
Figure 4: PCB pad design for various QFN



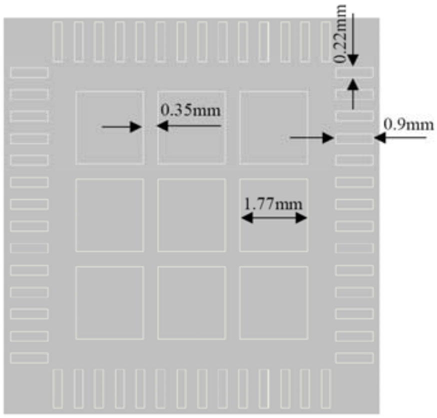
A: Stencil design for 5x5mm et-QFN



B: Stencil design for 5x5mm VQFN



C: Stencil design for 6x6 VQFN



D: Stencil design for 8x8 VQFN/HQFN

Figure 5: Stencil designs for solder paste printing

3. Experiment

3.1 Experimental Matrix Description

There are totally 9 legs of different QFN packages that will go through the TCoB test. Each leg contains a sample size of 33. Table 1 shows the experimental matrix. Leg1 is the control leg. Results of leg2 and leg6 can help to tell the effect of package size on solder joint reliability. Leg3 and leg4 can show the effect of lead-free (SnAg4Cu0.5) and eutectic solder. The difference between leg4 and leg5 is that all et-QFN samples in leg5 are attached with a metal lid to simulate possible application where further thermal dissipation performance is required. In this case, leg5 is to study the effect of such metal lid on solder joint reliability. Comparison of leg6 and leg7 will tell us the effect of punch-type and saw-type (with lead pullback design) on TCoB reliability. Lastly, we can know the effect of dummy die attachment for leg9 on solder joint reliability by comparing its results with leg8.

All the QFN samples use lead-to-lead wirebonding to form the daisy-chain connection on the package side. Together with daisy-chain traces on PCB, the continuity of the whole daisy-chain can be monitored. For current test, the PCB test board used is 6-layer with 2.35mm thickness and OSP pad finish.

3.2 Experimental Results and Discussion

Table 2 listed the test results. Fatigue cycles are 63.2% characteristic lives obtained from weibull plots.

Table 2: Experimental results for all QFN legs

Leg #	Pkg Type	Size (mm)	I/O	Die Size	Solder	Other info	Test Condition	N (63.2%)
Leg 1	VQFN-P	5x5	32	2x2	SnPb			N.A.
Leg 2	VQFN-P	5x5	32	2x2	Pb-free			3170
Leg 3	et-QFN-P	5x5	32	2x2	SnPb			1446
Leg 4	et-QFN-P	5x5	32	2x2	Pb-free		-40C to +125C 15mins-ramp 15mins-dwell	1484
Leg 5	et-QFN-P	5x5	32	2x2	Pb-free	with lid		1269
Leg 6	VQFN-P	6x6	40	2x2	Pb-free			3400
Leg 7	VQFN-S	6x6	40	2x2	Pb-free			2509
Leg 8	VQFN-S	8x8	56	4x4	Pb-free			2324
Leg 9	HQFN-S	8x8	56	4x4	Pb-free			2498

Leg2-VQFN-P VS. Leg6-VQFN-P: Effect of package body size

Leg2 and leg6 have comparable solder joint fatigue lives. Experimental results show that leg 6 is only slightly better than leg2 by 7%. This means that the effect of package body size does not show very clearly from the experiment. Subsequently, simulation will help to identify the better one.

Leg3-et-QFN-P VS. Leg4-et-QFN-P: Effect of lead-free solder

Leg4 with lead-free solder performs only slightly better than leg3 with eutectic solder by 3%. Note that et-QFN has a much lower fatigue life than the rest of QFN packages. This is because of the lacking of center pad soldering for et-QFN. For et-QFN, it center pad is exposed upwards and thus cannot be soldered onto PCB. This is why et-QFN has much lower fatigue life than other QFN packages. Also this may be the cause for the insignificant difference in fatigue life between lead-free and eutectic since both were highly strained in the test and failed early

Leg4-et-QFN-P VS. Leg5-et-QFN-P with Lid: Effect of lid attachment

The purpose of attaching a lid onto et-QFN is to simulate the end user condition where a lid may be used to better dissipate the heat. Its effect on solder joint reliability is seen that lid attachment will reduced the solder joint fatigue life by 15%.

Leg6-VQFN-P VS. Leg7-VQFN-S: Effect of punch- and saw- type (with lead pullback)

Solder joint reliability of leg6 is significantly higher than leg7, showing the strong advantage of punch type over saw type (with pullback) under same package size. Leg6 has no pullback design such that solder can wet the side surface of lead and help to constrain the CTE mismatching.

Leg8-VQFN-S VS. Leg9-HQFN-S: Effect of dummy die

Testing results show that leg 8 and 9 have almost equal reliability performance. Although there is dummy die attachment for leg9, which is expected to have larger CTE mismatch and thus cause poorer reliability, the solder directly under the die edge is the center pad soldering which is strong enough the absorb the extra mismatch caused by the dummy die. In this case, the solder joints at the periphery of package are not affected.

4. Simulation and reliability modeling

4.1 Constitutive and Fatigue Models

For lead-free solder joint reliability modeling, Schubert's hyperbolic sine constitutive model plus his creep strain energy based fatigue correlation model are found to give good prediction accuracy for BGA and CSP packages in study [2-3]. But for QFN solder joint reliability prediction, the accuracy of this approach is unknown. In the current work, Schubert hyperbolic sine solder constitutive model will still be used. The accuracy of his corresponding fatigue model will be examined. Schubert's constitutive model for lead-free solder and his accumulated creep strain energy density based fatigue model are listed in Table 3-5.

Table 3: Constitutive equations for lead-free solders

Solder	Constitutive equation
Sn3.8Ag0.7Cu Sn3.5Ag0.75Cu Sn3.5Ag0.5Cu (Schubert et al. [4])	$\dot{\varepsilon} = 277984[\sinh(0.02447\sigma)]^{6.41} \times \exp\left(\frac{-6500}{T(^oK)}\right)$

Table 4: Elastic material properties of lead-free solder [4]

E (MPa)	61251-58.5T (degree K) (Schubert et al. [4])
ν	0.36
CTE (ppm/K)	20.0

Table 5: Schubert's fatigue correlation model for his hyperbolic sine constitutive equation [4]

Acc. Creep Energy Density	$N_{cha} = 345 w_{acc}^{(-1.02)}$

4.2 FEA model

FE models were set-up using ANSYS FEA software. Figure 6-8 shows the typical meshes for various QFN packages. Due to symmetry, quarter models are used for all the simulations. Solder joint is modeled with 75μm stand-off height and six layers of elements. Three thermal cycles are modeled. As shown in Figure 9, simulation for leg9 predicts that the critical solder is at the package corner and crack is likely to occur between lead and solder. Same observations are found in the simulation results for all of the rest legs. Subsequent failure analyses for randomly selected samples from each leg confirm that solder joint cracks do lie between lead and solder as shown in Figure 10 and solder joints at the package corner register most failures. Based on those findings, accumulated creep strain energy was averaged over the top layer of elements as shown in Figure 11 for subsequent fatigue life predictions.

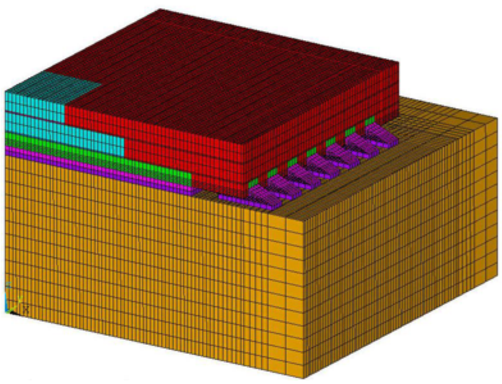


Figure 6: Overall mesh for leg9 (8x8 HQFN-Saw type without lead pull back design)

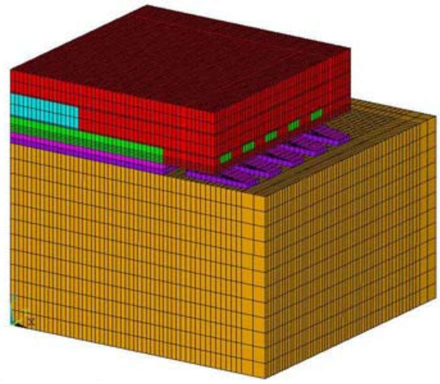


Figure 7: Overall mesh for leg7 (6x6 VQFN-Saw type with lead pull back design)

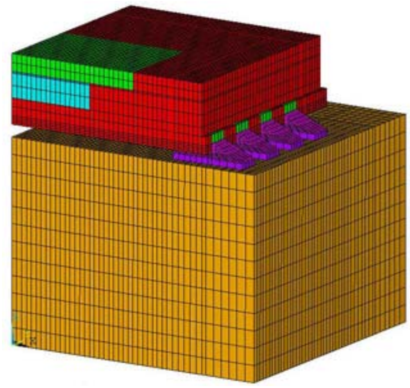


Figure 8: Overall mesh for leg4 (5x5 et-QFN-Punch type without lead pull back design)

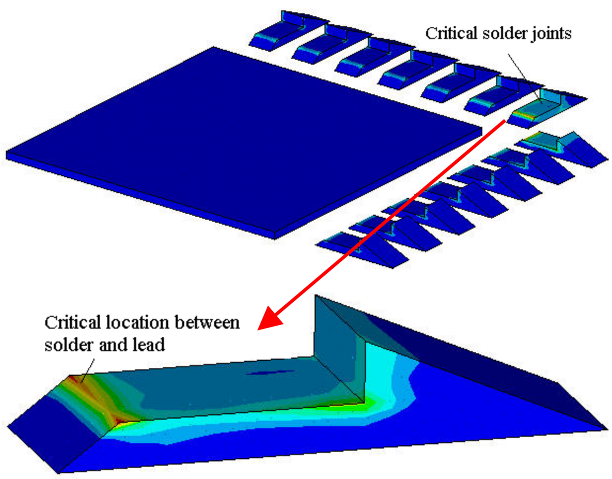


Figure 9: Accumulated creep energy distribution among all solder joints and critical solder joint

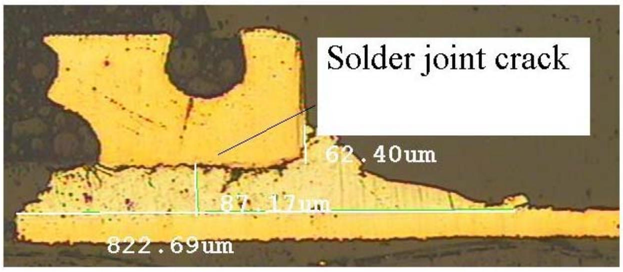


Figure 10: QFN solder joint cracking failure

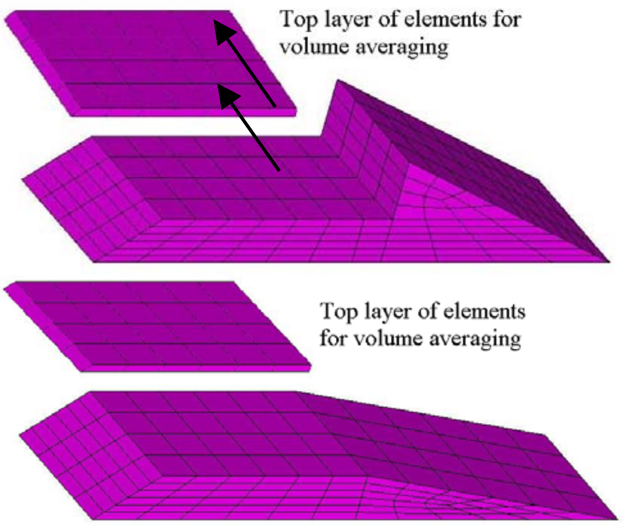


Figure 11: Layer of elements for accumulated creep strain energy averaging

4.3 Simulation results and discussion

The simulated solder joint fatigue life and experimental results are listed in Table 6. It is found that a large difference is there between the two. This probably means that Schubert fatigue prediction model cannot be applied in QFN cases. The constants in the power equation fatigue prediction model need to be adjusted for QFN solder joint reliability prediction. Based on the simulated accumulated creep strain energy density and the corresponding experimental result, a new curve fitted power equation is given in Figure 12. In Table 7, the predicted solder joint fatigue data are listed together with experimental results. It can be seen that the prediction error is within ±20%. Besides, the predicted results generally follow the trends shown in the experimental results. Therefore, the new curve fitted model can predict the QFN solder joint reliability with good accuracy.

Table 6: Solder joint fatigue prediction results using Schubert fatigue model

Leg #	Acc. creep strain energy (for top layer of element) per cycle	Experimental results	Schubert energy-based prediction model
2	0.0193	3170	18380
6	0.0350	3400	10533
8	0.0408	2324	9003
9	0.0409	2498	8998
7	0.0645	2509	5647
4	0.1071	1484	3367
5	0.2772	1269	1276

Table 7: Prediction accuracy of the new curve fitted fatigue prediction model

Leg #	Experimental results	Schubert energy-based prediction model	New curve fitted prediction model	Prediction error
2	3170	18380	3458	9%
6	3400	10533	2742	-19%
8	2324	9003	2582	11%
9	2498	8998	2581	3%
7	2509	5647	2160	-14%
4	1484	3367	1772	19%
5	1269	1276	1223	-4%

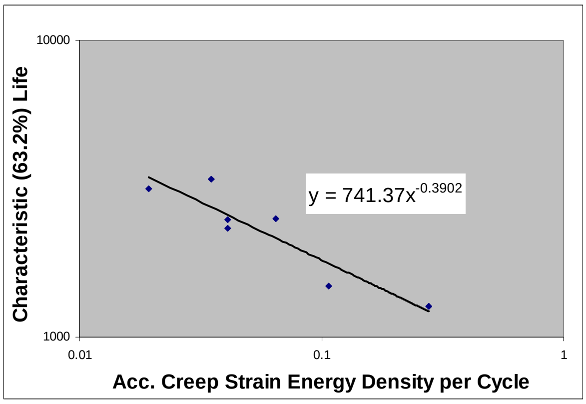


Figure 12: New curve fitted model for QFN solder joint fatigue life prediction

5. Summaries and Conclusions

In the current study, various QFN packages were subject to board-level temperature cycling test under -40C~125C with 15mins dwell/ramp. It is found that et-QFN, which has no center pad soldering to PCB, has much lower fatigue life than other QFN packages whose center large solder joints will significantly help to resist CTE mismatch under TCoB. Also for et-QFN, the attachment of heat spreader on top of the package can reduce the solder joint reliability, as this attachment makes the package rigid and pure shear between package and board is expected to be applied onto the solder joint, causing earlier failure.

Larger body size does not really enable longer board-level solder joint reliability although its center pad soldering is larger and number of peripheral leads is more. This is because larger body size also gives the peripheral solder joint larger distance-to-neutral-point effect.

QFN without lead pull-back design renders better solder joint shape and elongate reliability compared with pull-back design. This is because the solder fillet formation on the exposed side surface of peripheral leads helps to absorb CTE mismatch.

The effect of dummy die attachment for thermal enhancement in HQFN does not affect board-level solder joint reliability, although silicon material is known to be the major source of package/board overall CTE mismatch. This is because under the die influence area there is a large solder joint, thus the additional mismatch is absorbed by this part.

Based on the experimental results, simulation work was firstly performed to examine the applicability of Schubert's hyperbolic since constitutive model plus his fatigue model. However, the large discrepancy between simulation and actual results points out that Schubert's fatigue model does not apply to QFN solder joint reliability prediction. Therefore, a new power equation model is curve fitted. It is seen that the new model gives good accuracy. Thus, a accurate model for QFN solder joint reliability is established for future design and analysis.

6. Acknowledgements

The authors would like to thank UTAC R&D management team for their support. The assembly work done by process group for test vehicles preparation is also greatly appreciated.

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