FEA Study of Solder Hole Fill Impact on the Reliability of PTH Solder Joints

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Abstract
This paper is focused on the impact of solder hole fill on the reliability of the plated-through-hole (PTH) solder joints with different board thicknesses. Finite element analysis (FEA) is employed to understand the strain and stress of copper and solder with various solder fill percentages. The FEA prediction on fatigue life of copper barrel and solder joints are compared with experimental results, and the role of the pin wetted length (PWL) in PTH solder joint reliability is discussed in detail.

Introduction

PTH solder joints are widely used in electronics assemblies. As the through hole is copper plated and filled with solder, the stress due to in-plane thermal expansion mismatch between the component and the printed circuit board (PCB) is reduced to the minimum, and the only significant stress is from the vertical plane due to thermal expansion mismatch between the laminate and the plated copper wall in the z-axis, which could be very significant as the laminate materials usually have a z-axis thermal expansion at a magnitude one order higher than copper. As such, the integrity of PTH solder joints under thermal cycling is less dependent on the component length but highly dependent on the PCB thickness.

With increasing the board thickness and shrinking the hole size, the solder hole fill percentage is restrained during wave soldering and 100% hole fill is often impractical for thick boards. In that case, the impact of hole fill on the reliability of PTH solder joints becomes an important concern, and various studies using reliability testing have been performed in the industry [1~3]. In Ref. 1, the thermal cycling test results suggest that PTH solder joints with 30% hole fill in both 2.4 mm and 5 mm PCB boards have survived at least 3000 cycles from 0 to 100C air-to-air thermal cycling (referred to as “standard ATC”) without failure. Ref. 2 concludes that the pull strength of PTH solder joints are not impacted significantly after 2000 ATC cycles. It is also suggested that some degradation occurred when the PTH solder joints had been subjected to vibration at 9 g-rms and mechanical shock at 400 g but with no functional impact. Ref. 3 suggests that PTH solder joints at a thickness of 1.6mm have survived 3000 cycles from -40 to 125 ºC.

Because of the time and resource limitation, most of those thermal cycling tests were stopped at 3000 cycles, with no conclusion as to what PWL value or solder hole fill percentage is required for reliability.

In this work, FEA was employed to study the impact of the solder hole fill on PTH solder joint reliability in accelerated thermal cycling (ATC) and mechanical tests (including pull test and mechanical shock).

Experimental work and FEA Model Set-up

The test vehicle [1] is shown in Fig. 1a, which is part of a test board with a dimension of 406 mm x 305 mm. The test vehicle had up to 8 layers with a maximum of 6 copper ground planes as detailed in Fig. 2a. It is noted that the laminate is constructed with prepreg and core materials. In Fig. 2a, the material 7628 has a resin content of 42% and the material 2116 has a resin content of 56%. The hole size is 40 mils with a thickness of 25µm plated copper. Other types of hole size and copper thickness may also be used in the FEA study. Two board thicknesses (2.4 mm and 5.0 mm) and two board surface finishes (immersion silver and immersion gold) were included in the experimental work but only the results with immersion silver are used here in the FEA study. The connector has 40 pins with a square cross-section. A third board at a thickness of 3.1mm (125 mils) was also studied in the finite element model to compare the FEA results with testing data from other sources [2, 6].

The board was assembled using Sn-Ag-Cu (SAC) wave soldering process. The solder hole fill can be described in two ways: the PWL is the solder wetted length on the copper wall (excluding the pin protrusion part), and the hole fill percentage is defined by the PWL divided by the board thickness. Two hole fill conditions (100% and 30%) are shown in the cross sectioning picture (Fig. 1b). A quarter model of the connector was built as shown in Fig. 1c. To simulate the materials impact, the same structure as shown in Fig. 2a is used in the FEA model as shown in Fig. 2b.

For PTH via with no solder, the copper barrel is the only connection between two annular rings on the top and bottom of the PCB. Copper yields and creeps at certain stress and temperature as shown in Fig. 3 [4, 5], and a PTH failure results if a crack propagates along the whole circumference of the copper barrel. All other materials properties used in the FEA are shown in Table 1.

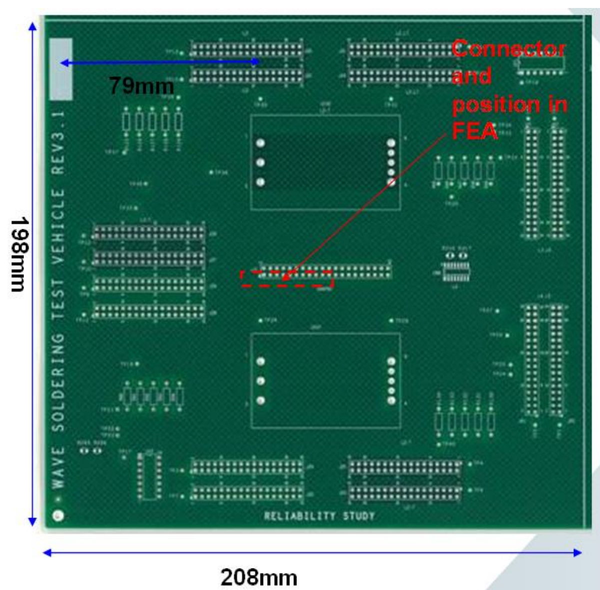
To investigate the integrity of the PTH and the solder joint, thermal cycling from 0 to 100 ºC was first conducted. The thermal cycling profile follows IPC 9701 Condition TC1, with 15 min. dwell, 15 min. ramp-up, and 60 min. total cycle time.

To estimate the life of copper barrel in the PTH, both plastic and creep strains need to be calculated and a Coffin-Manson equation is used (Equation 1).

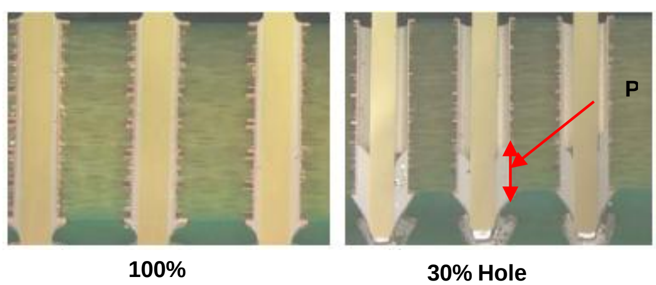
$$N_f = \varepsilon_f \left(\frac{2}{\Delta\varepsilon} \right)^{\frac{1}{0.6}} \quad (1)$$

where, ε_f=0.15~3.0 is the stress constant and $\Delta\varepsilon$ is the total inelastic strain range within a thermal cycle [4, 5]. It has been found that ε_f=0.15 gives a better fit in this study. Equation 1 may be used to predict the PTH failure at 63.2% failure rate.

For PTH solder joints, it is more complex as the PTHs are filled with solder and the copper barrel is covered by solder in the PWL area. With 100% solder fill, the PTH will fail only if the crack goes through both the solder and the copper. However, for partially filled PTH solder joints, copper failure in the non solder wetted area would mean failure for the PTH solder joint.



(a)



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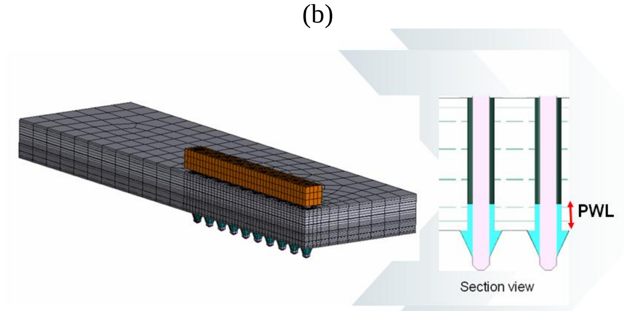


(c)

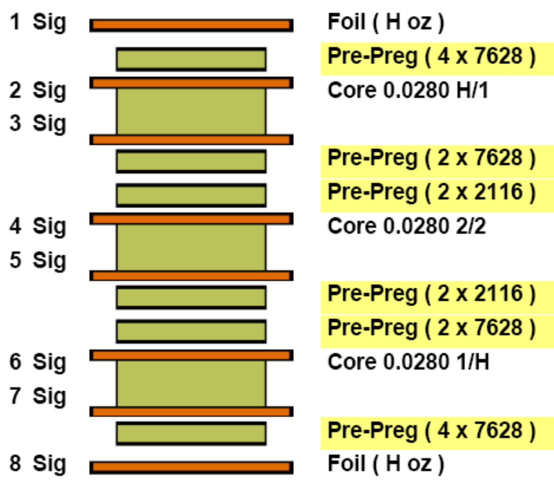
Fig. 1 (a) Test vehicle, (b) Cross sectioning view of PTH, and (c) FEA model including a connector

Nf (also referred to as B63 life) is the characteristic life which represents 63.2% failure. It is more convenient to use Bx life to describe a highly reliable product where B63 life is more than 10,000 cycles, i.e. B01 represents 0.1% failure which is widely used for high reliability products. As shown from test results [6], the PTH fatigue failure can be well presented using 2-parameter Weibull plot with beta>3.5, suggesting B01/B63≥0.139. In this study, B01/B63=0.139 is used to be conservative.

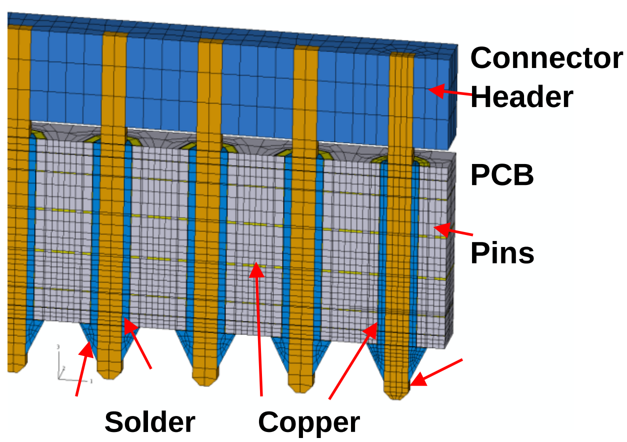
Results and Discussions

FEA Validation of PTH Vias

To validate the FEA modeling on the copper fatigue life, the PTH via without solder fill is modeled. The via sizes used in this study are 10, 13.5, 26 and 40 mils. The copper thickness is 15 um to be in line with the test results from HDPUG board [6]. The board thickness is 125 mils (3.1 mm). Three types of PCB materials are used here: Nelco N4000-6, Isola IS410 and IS420. The materials property details are shown in Ref. 6. The results are summarized in Table 2 as well as Fig. 4. As shown in Table 2 and Fig. 5, the error from FEA is 1~41%. This is acceptable considering that the experimental results have about 20% scattering [6].

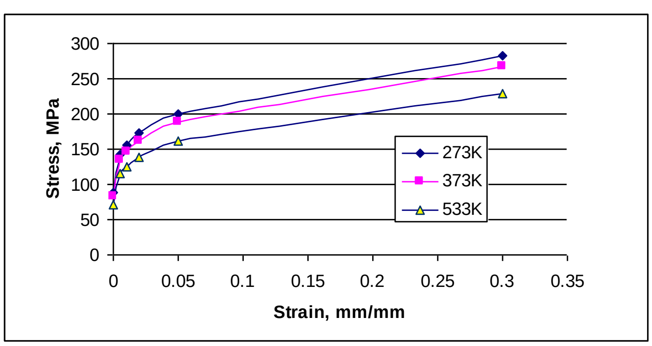


(a)



(b)

Fig. 2 Layer structure in the test vehicle (a) and FEA (b).



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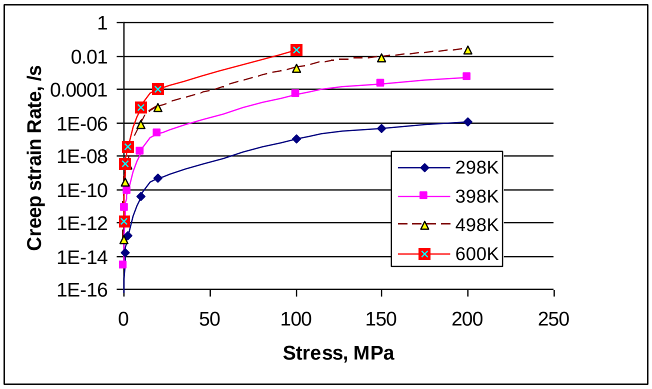


(b)

Fig. 3 Plasticity (a) and creep strain rate (b) of copper at different temperature.

Table 1 Materials properties used in the FEA

Struc-ture	Materials	Modulus, Gpa	Poisson ratio	CTE, ppm/C	Tg, C
pin	brass	115	0.29	18	--
copper	Cu	128	0.29	17	--
core	FR4	8.61/8.61/0.81 (0℃) 7.35/7.35/0.75 (155℃) 0.98/0.98/0.28 (190℃) (x/y/z)	0.11/0.14 /0.14 (x/y/z)	18/18/62(<Tg) 18/18/300(>Tg) (x/y/z)	150
Pin-head	EMC	114	0.29	22(95℃) 73(295℃)	--
solder	SAC	44.4	0.36	23	--

Note: All FEA simulation using the same FR4 materials in this table unless otherwise specified. Both plastic and creep for SAC solder may be considered during the ATC.

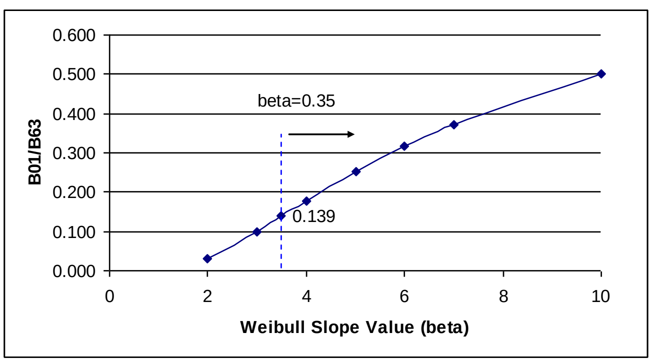


Fig. 4 B01/B63 vs. Weibull slope for PTH vias.

The simulated results of B01 for different via sizes are shown in Fig. 6, along with experimental results from HDPUG for 10, 13.5 and 26 mils. While no result is available from the HDPUG work for 40mils, in our testing we have demonstrated that no copper failure in PTH vias was found when the test was stopped at 4000 cycles, which is the case for both 2.4 mm and 5 mm boards. It is shown in Fig. 6 that the predicted failure of B01 life is generally higher than the testing results for larger via sizes. Fig. 6 also shows that a PTH via size over 26 mils should be used for thick boards (3.1 mm) to ensure that it can survive 3000 cycles without failure.

Table 2 FEA Results on PTH vias using different laminate values (10 mils via, PCB board thickness=125 mils)

CTE (<Tg), ppm/C	B63-Test(HDPUG)	B63-FEA	Errors of FEA
53	8016	11584	31%
62	5849	4988	-17%
63	3614	6164	41%
70	2649	2680	1%

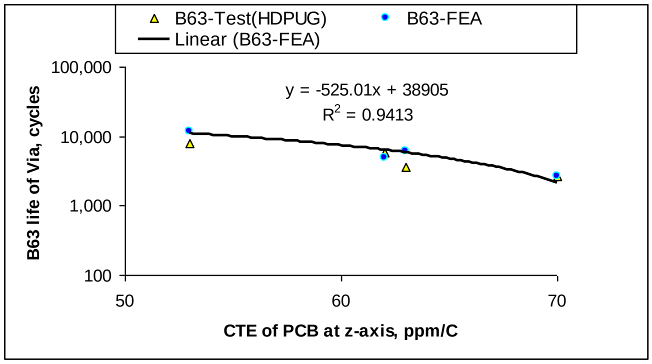


Fig. 5 Characteristic life of PTH vias by FEA in comparison with the testing results (3.1 mm board).

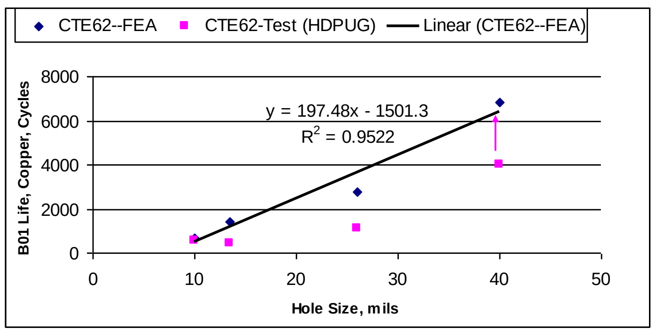


Fig. 6 Hole size impact on the via reliability (B01 life, CTE at z-axis=62ppm/C, 3.1mm board).

FEA Validation of PTH Solder Joints

A typical fatigue crack of the PTH solder joints are shown in Fig. 7. As indicated by the arrows in Fig. 7, the cracks usually start from the solder intersection with the copper barrel or from the interface between the solder and the annular ring. These are also locations with the highest strain concentration during thermal cycling. The life prediction on the surface mount solder joints under thermal cycling has been available with support of experimental work; Darveaux's fatigue crack model [7-8] can be used to simulate the ball grid array and other SMT solder joints. Equations (1) and (2) represent the damage model for solder crack propagation.

$$N_0 = K_1(\Delta W)^{K2} \quad (2)$$

$$\frac{da}{dN} = K_3(\Delta W)^{K4} \quad (3)$$

$$N_f = N_0 + \frac{a}{da/dN} \quad (4)$$

$$N_{ff} = \frac{N_f}{2} \quad (5)$$

where

N_0 is the crack initial life;

N_f is the crack propagation life;

N_{ff} is the failure free time;

ΔW is the average strain energy density consumption within a thermal cycle;
a is the length of crack path; and
K1, K2, K3, and K4 are model constants.
In Equation 4, the fatigue life is the sum of the crack initiation life and crack propagation life. As suggested by Han et al [9] and Ng et al [10], the portion from crack initiation life is negligible. This is also true from the observation of the thermal cycling test on PTH solder joints in this work [1]. Usually, the PTH starts to crack before 1000 cycles but does not become open until after 4000 or even 6000 cycles.

To validate the FEA simulation, a 2.4 mm PCB with different solder hole fills was used, as it was the only case in which test failures occurred. Fig. 8 shows the cross section of a PTH solder joint failure from the thermal cycling test [1]. PTH solder joints failed at 1256 cycles for a low PWL (<16 mils), and no PTH solder joints failed for PWL>47 mils (1.2 mm). The prediction from FEA is listed in Table 3 (*with no pin protrusion*). As shown in Table 3, the average strain energy density for PWL=16 mils is quite large and the predicted failure free cycle is only 320 cycles (B63=640 cycles). For PWL=47 mils, the strain energy density has dropped below 0.011MPa giving predicted failure free life over 10,000 cycles. The tested results from this work show no failures or signs of failures up to 4000 cycles.

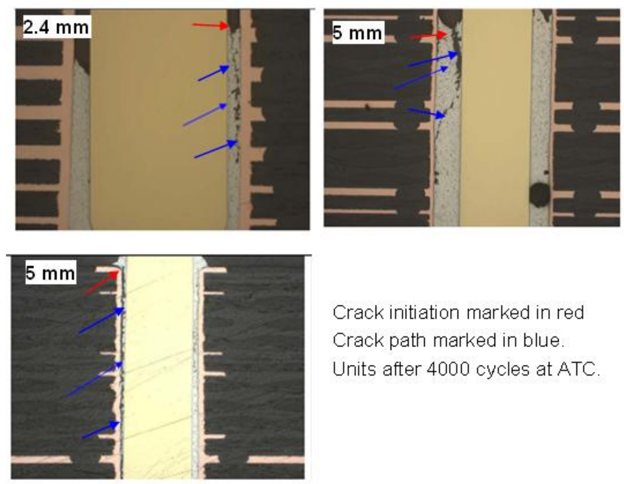
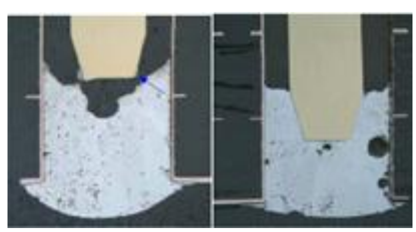
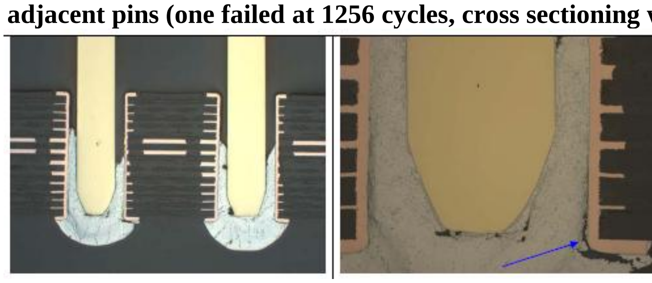


Fig. 7 Cracking of PTH solder joints after 4000 ATC cycles.



(a) PWL=15~25 mils, two adjacent pins (one failed at 1256 cycles, cross sectioning was done at 3000 cycles)



(b) PWL=1.2 mm (47mils).

Fig. 8 PTH solder joint failures (a) and non failure (b). Note: board thickness=2.4 mm (94 mils) and no pin protrusion,

Table 3 Life estimation of PTH solder joints (FEA vs. testing). (PCB board thickness=2.4 mm, no pin protrusion, thermal cycling from 0 to 100 ºC)

Board thichness	Hole Fill Percentage	PWL, mils	Solder Failure Free, cycles	Average Strain Energy, MPa	First Failure in Testing
2.4mm, without pin protrusion	10%	16	320	0.143	1256
	30%	30	8,974	0.041	>3000
	50%	47	>10000	0.011	>4000
	100%	94	>10000	0.0081	>4000

Note: Assume K1=0, K3=0.0065, K4=1.4613 [9]

Life Estimation on the Copper Barrel during ATC

Once the PTH holes are filled with solder, the strain distribution has changed. Figure 9 shows typical strain concentration for different hole fills for a 5 mm PCB. The highest strain location is right above the PWL area, which is the same as the location where the solder crack initiates (Figure 7). The B01 life of copper barrel for various solder holes is simulated by FEA and then calculated using Equation 1. The results as shown in Fig. 10 indicate that the B01 life varies from 728 cycles up to over 10,000 cycles, and is usually the highest at either 0 or 100% solder hole fill. This is because the bare PCB (no solder) can deform more freely, whereas for 100% solder fill, the copper barrel is fully protected by the solder. As expected, a thicker board (5 mm) has lower B01 life than a thinner board (2.4 mm and 3.1 mm). The lowest B01 is around 50% hole fill for 2.4 mm and 3.1 mm boards but around 10% hole fill for a 5mm board. It is noted that for the 5 mm thick board, the B01 life may be less than 1000 cycles when the PWL is less than 47 mils depending on the laminate materials used.

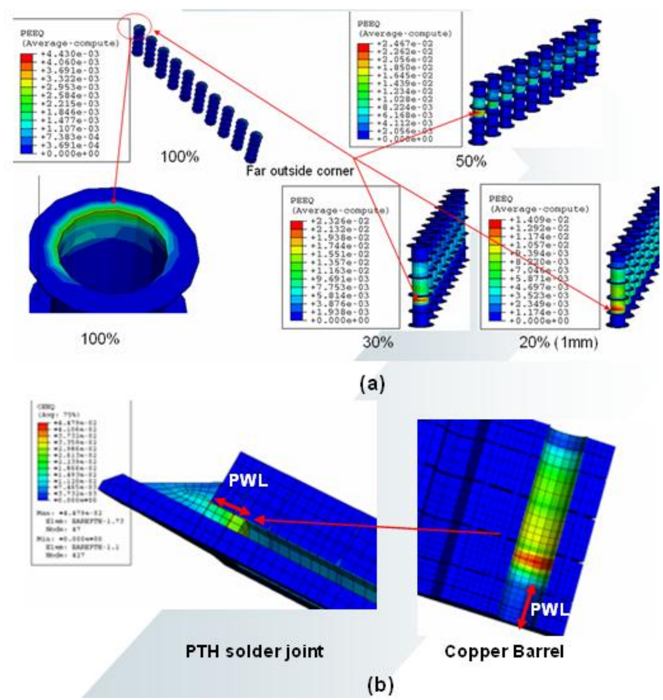


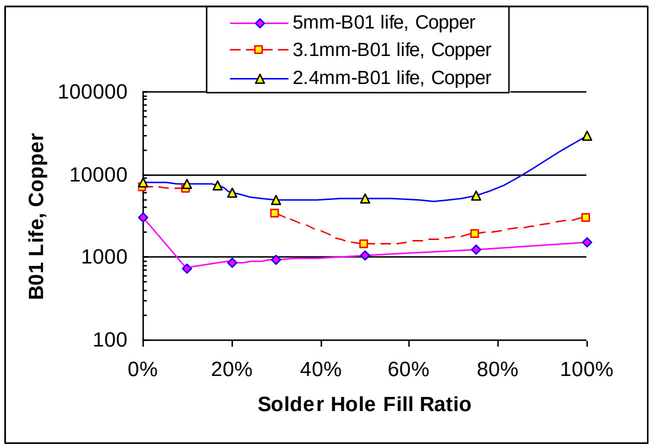
Fig. 9 Inelastic strain concentration on the copper barrel for various hole fills (a) and zoomed view of 10% hole fill case (b) under thermal cycling (5mm PCB).

Risk Assessment on the Solder Failure during ATC

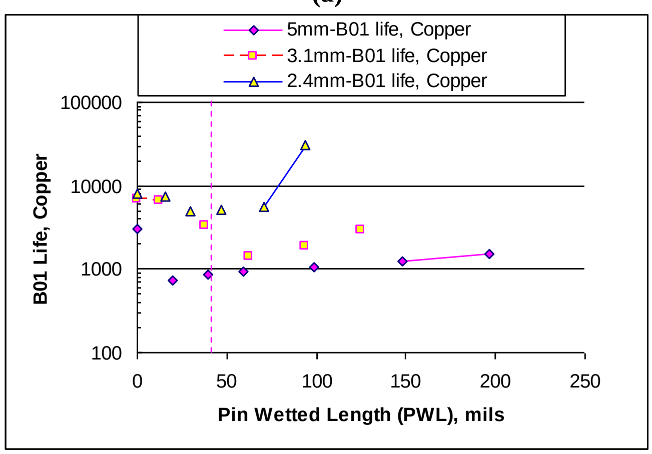
Solder failures are assessed using FEA in conjunction with Equations 2~5. Three board thicknesses are used: 5mm, 3.1 mm and 2.4 mm. The results are summarized in Table 4. As shown in Table 4, the values of average strain energy density of the PTH solder joints are very small except for PWL≤30 mils. In all cases in Table 4, the failure free life of the PTH solder is over 10,000 cycles. When compared to that in Table 3 (*with no pin protrusion*), the PTH solder joints in Table 4 (*all with pin protrusion*) show significantly lower solder joint stress in the PWL region.

Table 4 Solder failure free life and its impact from hole fill.

Board thichness	Hole Fill	PWL, mils	Solder Failure Free, cycles	Average Strain Energy, MPa	First Failure in Testing
5mm, with Pin Protrusion	15%	30	>10000	0.0234	>4000 cycles
	30%	59	>10000	0.009	
	50%	98	>10000	0.010	
	75%	148	>10000	0.005	
	100%	197	>10000	0.0059	
2.4mm, With Pin Protrusion	17%	16	8,938	0.020	>4000 cycles
	31%	30	>10000	0.0205	
	50%	47	>10000	0.00833	
	75%	71	>10000	0.00609	
	100%	94	>10000	0.00396	



(a)



(b)

Fig. 10 B01 life of copper barrel in PTH solder joint with various solder hole fill (a) or PWL (b). all with pin protrusion.

Pull Test Analysis of PTH Solder Joints

Pull test is usually required on PTH solder joints. A pull force is applied on the pin in the z-direction (Fig. 11). As shown in Fig. 11, the plastic strain is reduced drastically for PWL>47 mils.

According to test results by Ferrer et al [2], the pull force, σ in lbf, of PTH solder joints, is linearly correlated with PWL.

$$\sigma = 7.79+0.154*PWL \qquad (6)$$

Considering the geometry and solder impact gives

$$\sigma = A\tau*(87.7+40)*PWL \qquad \textbf{(7)}$$

where:
A=0.5 (by curve fitting ;)
87.7 (mils) is the perimeter of the solder around the connector pin;
40 (mils) is the pin protrusion length; and
τ=0.0044 MPSI (which is the shear strength of the solder).

The pull force can then be plotted with the PWL in Fig. 12, with a lower bound curve using 3σ (assuming that the standard deviation σ is 10% of the mean value). It shows that PWL>8 mils shall be sufficient to meet the minimum of 5 lbf [2]. In considering both Fig. 11 and 12, a minimum PWL of 47 mils shall be adequate to meet the pull test requirement.

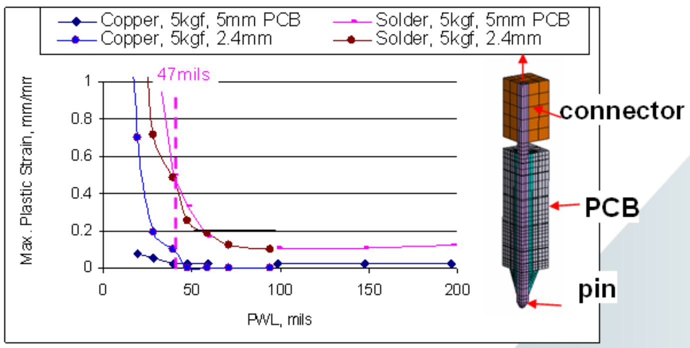


Fig. 11 Plastic strain vs. PWL at various board thicknesses at a pull force of 5 kgf (1 kgf=2.247 lbf).

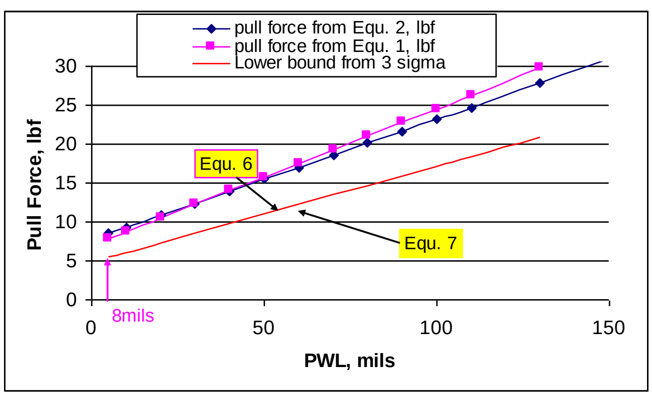


Fig. 12 Impact of PWL on pull force from empirical calculation.

Mechanical Shock Analysis of PTH Solder Joints

Mechanical shock and vibration tests are also required to qualify the electronics assembly. A shock with acceleration at a maximum peak value of 400 G is normally required for telecommunication products [2]. A higher acceleration may be needed for handheld devices and certain other applications. To simulate the mechanical shock for the test vehicle, acceleration is applied on corners and edge centers of the board (Fig. 13). The shock duration per cycle is 1ms per mil-std-883F, Method 2002.4. The acceleration load is applied to the four points as shown in Fig. 13, using a sine wave as shown in Fig. 14, assuming that the shock is applied in both directions. Two acceleration levels are applied: 400 G and 1500 G.

It can be learned from Fig. 14 that the solder does not yield at 400 G for a thickness of 3.1 mm board, indicating that the PTH solder joints will not be significantly impacted by the mechanical shock if the acceleration is at 400 G or below. However, the PTH solder joints do yield if the board thickness decreases to 2.4 mm as shown in Fig. 15. Fig. 15 shows that a maximum plastic strains of 0.1% at both solder and copper barrel are achieved for 2.4 mm board with 20% hole fill (which is considered as one of the worst case scenarios). This value is insignificant as the mechanical shock test is normally performed in the range of 10 to 100 cycles. However, this does show that the mechanical shock performance is highly dependent to the board thickness.

To assess the design margin for mechanical shock with different hole fills, mechanical shock test simulation is performed at an acceleration of 1500G; the plastic strain is about 2% from one cycle. Typical strain distributions are shown in Fig. 13 for various board thicknesses. It is noted that the plastic strain distribution on the copper barrel is impacted by the solder hole fill percentage. At lower percentages of solder hole fill, the highest plastic strain is located at the top surface. It moves to the solder intersection with the copper barrel when the solder hole fill is 30% and above.

Prediction for copper barrel fatigue life at 1500 G is also attempted assuming that it follows the same Coffin-Manson equation (Equation 1). However, the constant, ε_f, could be different in mechanical shock as compared to thermal cycling. In order to compare the solder hole fill impact, a normalized B63 life based on 100% hole fill for a 2.4 mm board is employed. The reason to use 2.4 mm is that 2.4 mm usually is the thinnest board within the scope of interest in this study and represents the worst case for shock and vibration performance. For the solder failure life, Equations 2~5 is still valid; however, a different coefficient K3 and K4 should be used, which are usually determined by experimental work. For the mechanical fatigue under vibration shock, Syed [12] suggests K4=1.44. This suggests that K4=1.46 in Equation 5 may be still valid for mechanical cycling.

The predicted number of shocks to failure at 1500 G for the copper barrel and solder are illustrated in Fig. 16. In Fig. 16, all B63 lives over 1 are truncated to 1.0 in order to concentrate on the lower PWL region. A predicted life B63=1 represents that the reliability under mechanical shock is equivalent to that of a 2.4 mm board with 100% hole fill. As shown in Fig. 16a, the number of shocks to failure of the copper barrel in the PTH solder joints is affected by the solder hole fill; there is a valley in the curve at around 25 mils (0.6 mm) for 2.4 mm and 3.1 mm boards, as a lower solder hole fill would generally increase the stress of the copper barrel. However, the stress of the copper barrel is not affected negatively if the solder hole is so low that the connector joints are acting as a rigid fastener. For solder failures as shown in Fig. 16b, the fatigue life decreases with decreasing PWL as expected. However, they performed slightly different among the three types of boards. For the 2.4 mm board, the number of shocks to failure for the solder is not impacted significantly by the solder hole fill when PWL<50 mils. For the 3.1 mm and 5 mm boards, the fatigue life decreases greatly when the PWL is below around 30 mils. This shows that for a board thicker than 3.1 mm, PWL≥ 60 mils is needed to ensure that the mechanical shock performance is not degraded as compared to that of the 2.4 mm board with 100% hole fill. However, that does not mean that 47 mils is not sufficient to meet the mechanical shock performance for all three board thicknesses. When calculated using Equation 1, the B63 life for the copper barrel for the 2.4 mm board with 100% hole fill would be more than 5,000 cycles at 1500 G. This number would increase exponentially if the maximum shock level is only 400 G. This suggests that a minimal PWL of 47 mils is still valid for most applications.

It is to be noted that the mechanical shock and vibration performance is also highly dependent on the component structure as well as the board structure (including the loading and fastening), so the cases studied in this work may not represent the worst case. A more detailed investigation is needed for cases with heavy components for high mechanical reliability applications. On the other hand, PWL>47 mils may not be needed for less demanding applications.

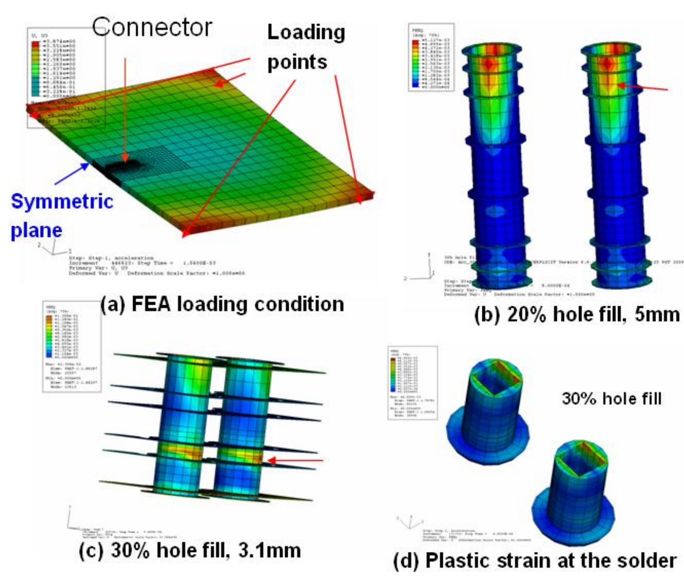


Fig. 13 FEA models for mechanical shock at 1500 G.

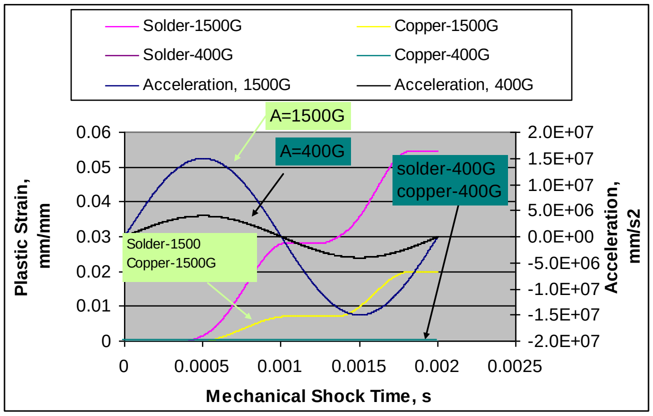


Fig. 14 Response of maximum plastic strain of PTH solder joints from mechanic shock (3.1 mm board).

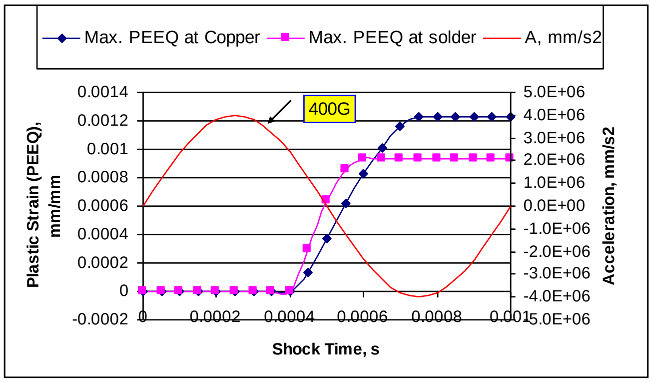
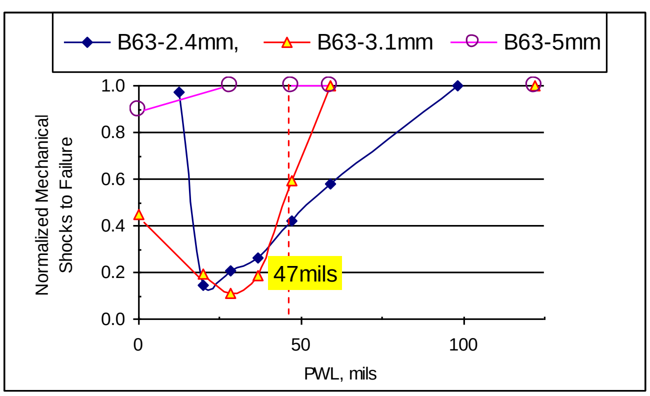


Fig. 15 Response of maximum plastic strain of PTH solder joints from mechanic shock at 400 G (2.4 mm board).

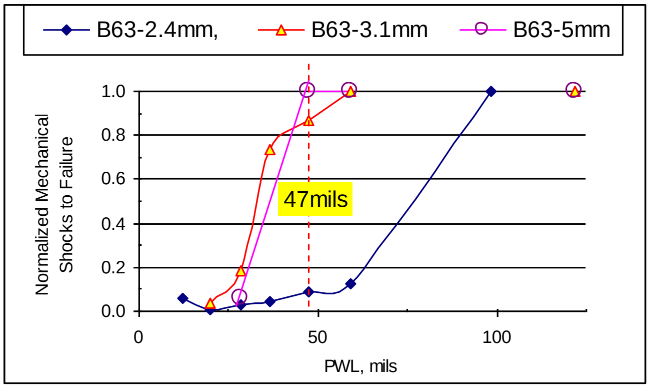
SUMMARY

The FEA results obtained agree reasonally well with the testing results. Based on the results from this study, a minimum of 47 mils PWL should be sufficient to meet the reliability requirements for thermal cycling and mechanical pull/shock for most commerial products as long as the PTH has pin protrusion and proper laminate materials are selected. It is found that the thermal cycling reliability of the copper barrel is very sensitive to the board thickness and the CTE of the laminate materials. For example, for a thick board (~5 mm) along with a laminate material with a high z-axis CTE (62 ppm/ºC in this study), the copper barrel may crack when subjected to 1000 cycles of standard ATC. On the other hand, the solder joint is less impacted by the board thickness and/or laminate materials. With no pin protrusion, there is a failure risk when the PWL is less than 16 mils for a 2.4 mm board.

Both the solder and the copper barerel are expected to pass the pull test at 5 lbf for PWL >8 mils. For the mechanical shock test, the reliability requirement can be met for most applications with PWL > 47mils with a board thicker than 3.1 mm. Further study is in progress on mechanical shock and random vibration with worst case scenarios.



(a)



(b)

Fig. 16 Life prediction for copper barrel (a) and solder (b) for different board thicknesses and PWL under mechanical shock at 1500 G

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