Reliability Analysis of Pin-in-Hole Solder Joints

Model predictions addressed a sequence of multiple environments that encompassed handling, transportation, and use segments within the assembly lifetime

BY P. T. VIANCO AND
M. K. NEILSEN

A reliability assessment was made of the thermal mechanical fatigue (TMF) resistance of defective through-hole solder joints on an encapsulated printed wiring assembly (PWA).

Printed Wiring Assembly

A schematic diagram is shown in Fig. 1 of a "nontypical" PWA that has components — resistors, capacitors, etc. — "sandwiched" between two through-hole printed wiring boards (PWBs). Some components had the leads soldered to one PWB with 63Sn-37Pb (wt-%) alloy; others had one lead soldered to each of the two PWBs using the same solder. The internal volume and external regions around the PWBs were encapsulated with a glass microballoon-filled epoxy to enhance the assembly's resistance to mechanical shock.

Solder joints exposed to temperature cycling environments can experience thermal mechanical fatigue (TMF) degradation that eventually leads to cracked joints and an electrically open circuit. Partially filled solder joints pose an unknown reliability risk especially in the presence of an encapsulant and the complex configuration in Fig. 1. This circumstance warranted the use of the solder fatigue computational model to predict the risk posed by the defective interconnections to the reliability of the PWA (Refs. 1, 2).

The computational modeling analysis began with the development of appropriate finite element meshes of the various PWA constructions. Then, the model was exercised to predict TMF of the solder joints, taking into account the multiple temperature cycling conditions that occur during handling, transportation, and use. Two failure criteria were established that were based on the number of temperature cycles required to initiate a TMF crack or cause 100% cracking that causes an electrical open.

Setup of the Model

Finite Element Model. The blue resistor in Fig. 1 was selected because its configuration was more prone to TMF in its solder joints. The development of the finite element model is illustrated in Fig. 2 for the blue resistor in Fig. 1. Figure 2A shows the resistor body, the solder joints, and the bottom PWB to which the solder joints were made.

The introduction of the second, top PWB and the encapsulant are shown in Fig. 2B. The encapsulant is located between the PWBs as well as underneath them; it was left out from above the top PWB because it had minimal effect on the TMF of the blue resistor's solder joints.

The presence or absence of encapsulant from underneath the bottom PWB affected the fatigue of the solder joints. This case, which is shown in Fig. 2C, addresses the worst-case scenario of a void having developed in the encapsulant.

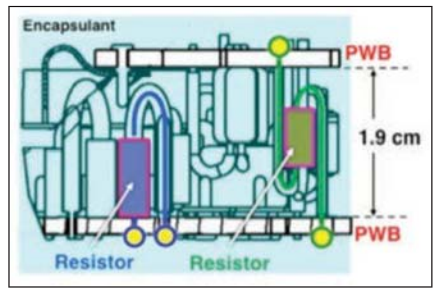

Fig. 1 — Schematic of the PWA. The components are attached to one PWB (blue resistor) or to both PWBs (green resistor). The interior volumes and areas above and below the PWBs were filled with an encapsulant.

The two solder joints of the resistor are labeled "1" and "2." Preliminary modeling predictions indicated solder joint 1, directly under the component, experienced a greater degree of TMF due in large part to the interaction between the resistor body and the encapsulant. Therefore, the finite element model considered only joint 1.

The need to address only a single solder joint allowed for the finite element model, which at this point had cylindrical symmetry, to be reduced further to a 10-deg "pie slice" geometry as shown in Fig. 3. The predictions

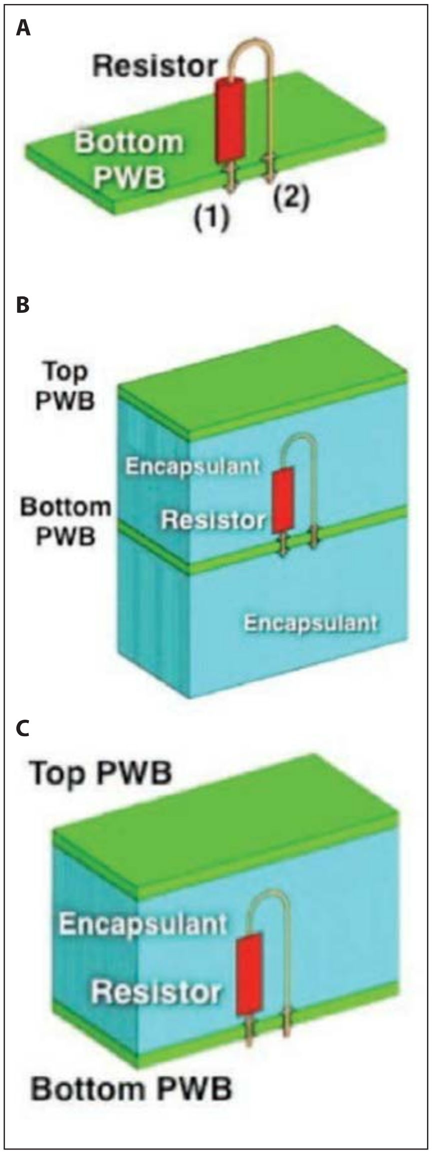

Fig. 2 — Solid models show the single symmetry plane of the assembly: A — Resistor, its solder joints (labeled 1 and 2), and the PWB; B — both PWBs and the encapsulant located between them and underneath the bottom PWB; C — the same as B except the encapsulant was eliminated from underneath the bottom PWB.

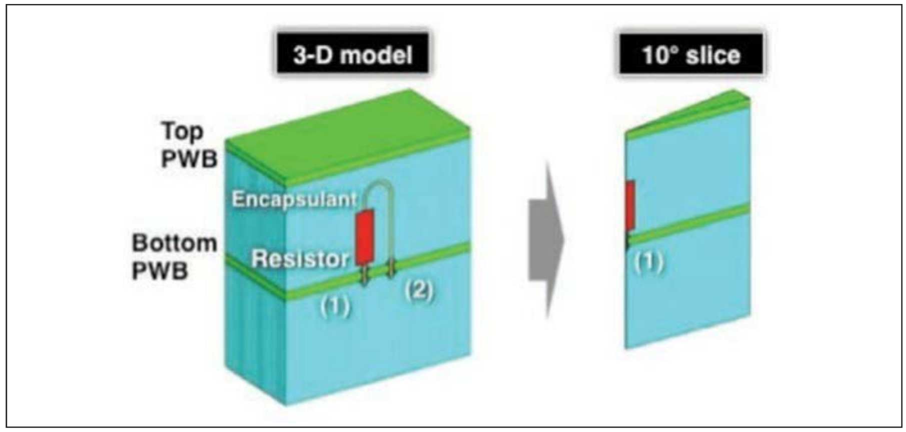

Fig. 3 — The 3-D finite element model (left) is reduced to the 10-deg slice model (right) by considering only joint 1.

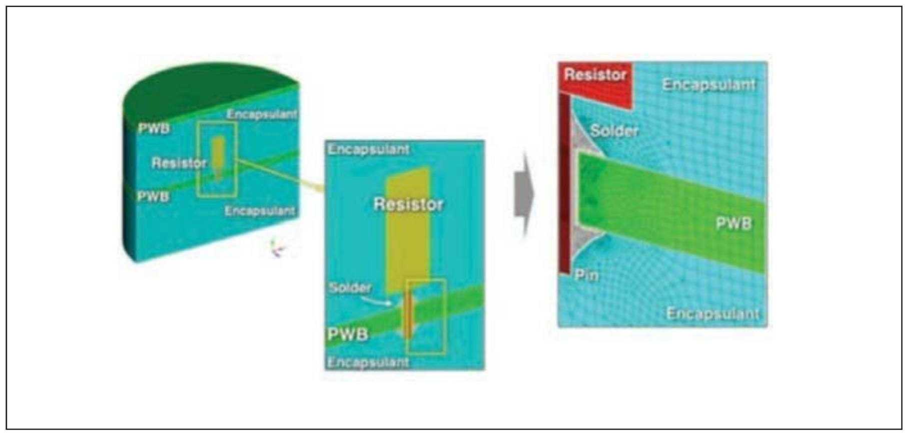

Fig. 4 — The 3-D solid model of the 1 joint is shown at left. The finite element mesh of the 10-deg slice is shown to the right.

retained adequate fidelity.

The finite element construct shown in Fig. 4 represents the baseline case having full fillets on both sides of the joint. The initial 3-D solid model is shown at left and the 10-deg-slice finite element mesh is presented at right.

The computational model analyzed four variations of hole fill. The finite element meshes illustrated in Fig. 5 are 100, 75, and 50% hole fill, respectively. Figure 5D shows the case of encapsulant being absent from under the PWB and the 50% hole fill. The missing solder was replaced by encapsulant in the holes (magenta arrows).

Temperature Cycle Conditions. The temperature cycling condition experienced in service had three segments. There are two transportation and handling segments, #1 and #2, as well as the final use segment. The details of the three segments are listed below, including the minimum and maximum temperature limits, which define temperature range, ΔT; hold times at temperature limits; the ramp rates between the limits; and number of cycles:

- Transportation and handling segment #1: –29°C/49°C; 10-h holds; 2 h/ramp; 15 cycles;
- Transportation and handling segment #2: –18°C/49°C; 10-h holds; 2 h/ramp; 15 cycles;
- Use segment: 16°C/33°C; 1 cycle/year; sinusoidal between limits; 60 cycles (years).

The following methodology was used to predict the total percentage of TMF used up by the combination of serial environments. The analysis began with the transportation and handling segment #1 (–29°C/49°C; 24-h period). Crack initiation is the failure criterion, which is designated with the subscript, i. The computational model calculated the number of cycles required to reach crack initiation under the transportation and handling segment #1, $N_{i,\#1}$, to be 3600 cycles. However, the solder joints will experience only 15 cycles under segment #1. Therefore, the fraction of TMF life used up by the 15 cycles is 15/3600 = 0.0042. The same computation is made for transportation and handling segment #2 as well as for the use segment.

The total percentage of TMF life consumed by the service environment is the sum of the percent lifetimes used up by the three segments. This methodology is referred to as Miner's Rule. Mathematically, that summation is expressed by Equation 1:

$$\text{Total \% Life Used (service)} = [(15/N_{i;\#1}) + (15/N_{i;\#2}) + [60/N_{i;use}]] \times 100 \quad (1)$$

A similar equation was developed for the failure criterion of a 100% crack that would lead to an electrical failure. These two equations were applied to each of the five solder joint configurations represented in Fig. 4D (baseline) and Fig. 5 (variants of hole fill).

Results – Model Predictions

The results are presented in Table 1 for the service environment that included the two transportation and handling segments, #1 and #2, as well as the use segment. The first row is the baseline condition. The model predicts that 0.66% of the solder joint's TMF life is used up by the time the interconnection reaches the end of service, based upon the crack initiation criterion. When the failure criterion is 100% cracking, then 0.18% of the fatigue life is consumed at the end of service. (Note: The percentage of fatigue life used to reach 100% crack formation is because for the same number of cycles in the service environment (numerator), more cycles are required to reach 100% crack failure (denominator) than crack initiation.)

Clearly, these percentages, as well as those of the other hole fill configu-

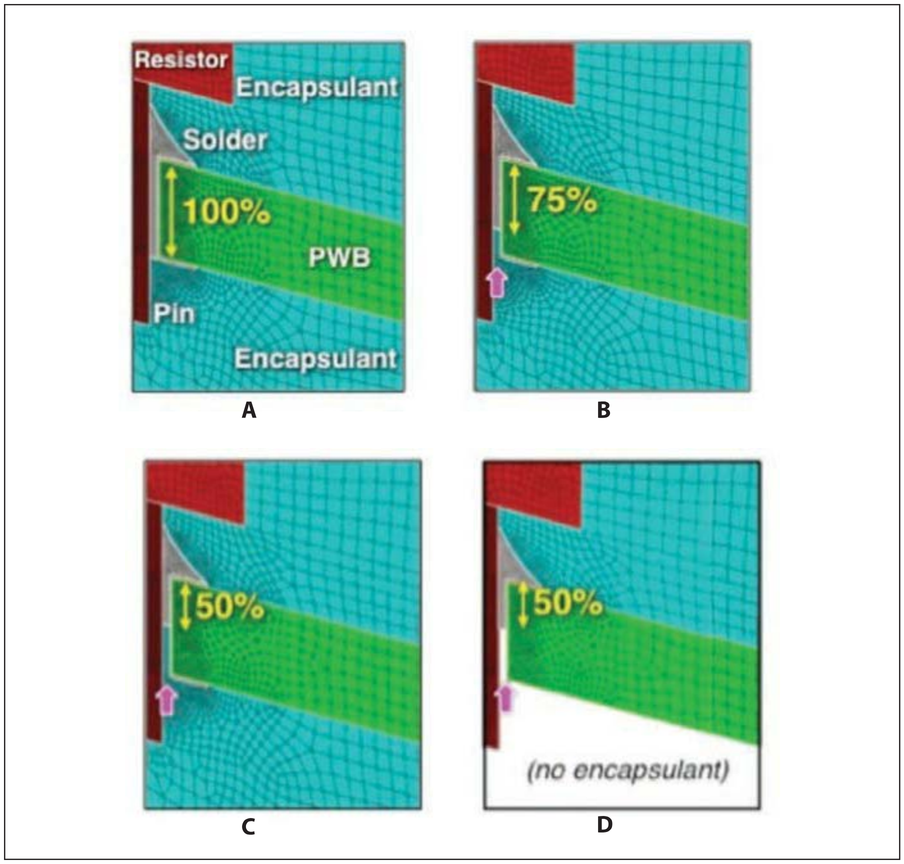

Fig. 5 — The 10-deg-slice finite element models are shown for the cases examined by the computational model: A — 100%; B — 75%; and C — 50% hole fill. D — The fourth variant has encapsulant absent from under the PWB and 50% hole fill. The magenta arrow signifies missing solder was replaced with encapsulant.

rations are very small. All of the solder joint configurations have ample margin to resist TMF failure under the service environment. This conclusion, which is valid even when a 2 or 3× safety factor is added to the computations, illustrates the inherent robustness of through-hole solder interconnections.

Referring to the other configurations in Table 1, the case of 100% hole-fill (single fillet on one side) had a TMF lifetime similar to the baseline case with two fillets. Thus, the loss of the bottom side fillet was relatively inconsequential to the TMF lifetime. The TMF remained very small when the hole fill was reduced to 75% and 50%. The observation was made that the fractional change in TMF life calculated between the 100% and 50% hole fill conditions differed between the crack initiation and 100% cracking criteria. This trend indicates the TMF deformation, which leads to crack initiation, does not scale the same as the TMF deformation-plus-cracking process that leads to a fully cracked interconnection.

The absence of encapsulant from underneath the bottom PWB (Fig. 5D) caused nearly an order of magnitude increase of TMF damage to the joints. Although the 3.9% and 1.7% loss of fatigue life for the two respective failure criteria appear to be small, they be-

Table 1 — Percent of Life Used Up in the Service Environment Based Upon the Two Failure Criteria of Crack Initiation and a Complete Crack through the Joint

Through-Hole Configuration	Percent of Life Used to Crack Initiation (%)	Percent of Life Used to a Complete Crack (%)
Full fillet, both sides	0.66	0.18
100% hole fill	0.65	0.20
75% hole fill	0.73	0.28
50% hole fill	0.94	0.33
50% hole fill; No bottom encapsulant	3.9	1.7

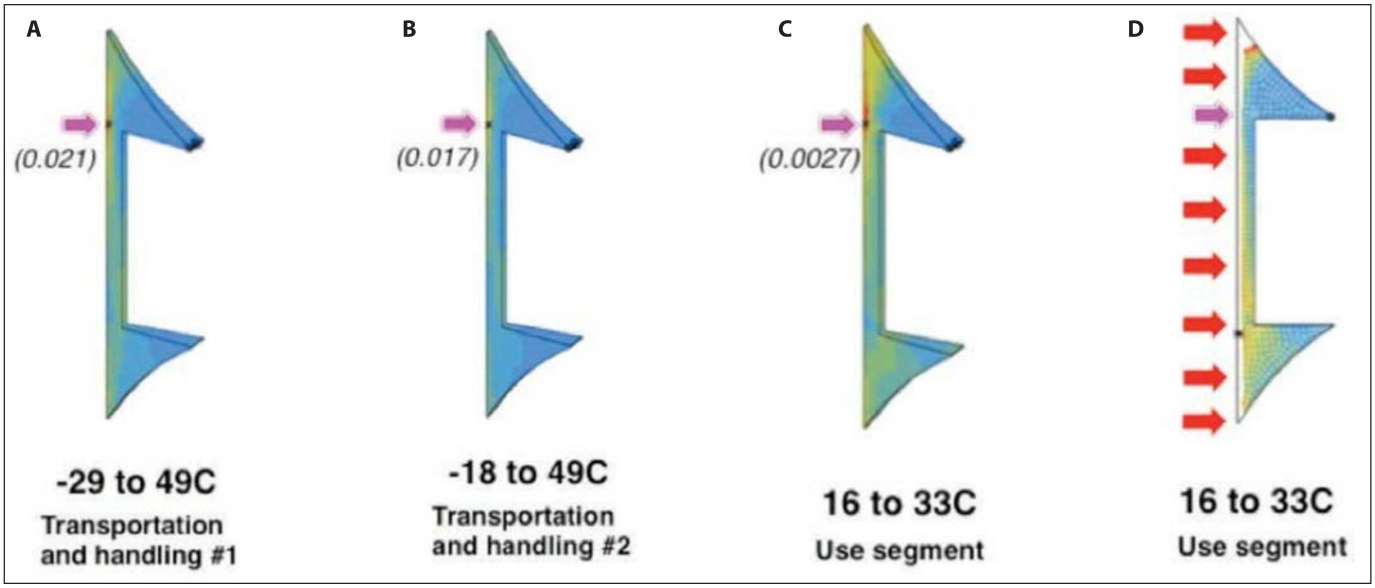

Fig. 6 — A–C — Computational-model predictions are shown of TMF strain contours for the baseline configuration (full fillet, both sides) resulting from a single temperature cycle of transportation and handling segments #1 and #2 as well as the use segment as noted below each picture. The magenta arrow indicates the location of greatest fatigue strain; the latter's magnitude is noted in parentheses. D — The contour diagram shows the case of the 100% crack (electrical open) resulting from the TMF that initiated per the use segment in C. The white elements, which are indicated by the red arrows, represent the cracked material.

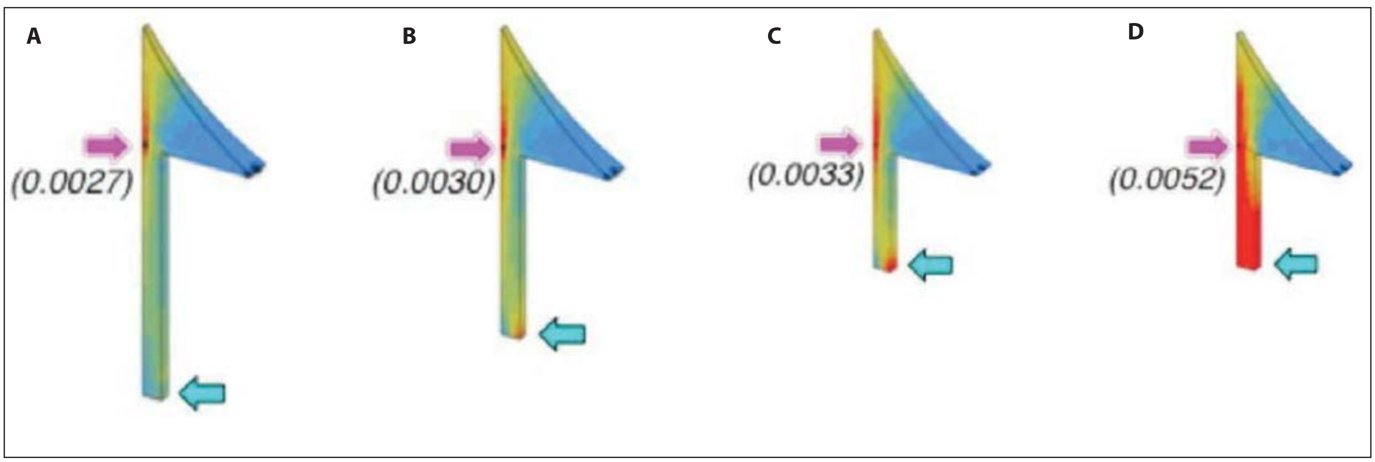

Fig. 7 — Computational-model-generated strain contours of the single use segment cycle (16°C/33°C; 1 cycle/year) for the following hole fill conditions: A — 100%; B — 75%; and C — 50%. D — The strain contours are shown for the case of 50% hole fill, but in the absence of encapsulant under the PWB. The magenta arrows indicate the location of greatest strain (value in parentheses). The cyan arrows point out the bottom terminus of the hole fill.

come significant when multiplied by the aforementioned safety factors.

The computational model also predicted the TMF strain distribution within the solder joint geometry. Shown in Fig. 6A are strain contours for the baseline solder joint (full fillets, both sides) caused by a single cycle of the transportation and handling segment #1. The magenta arrow indicates the location of the highest such strain (0.021) and, as such, is the location of TMF crack initiation. That location of greatest strain was near the top of the joint, not at the mid-plane location. This behavior was caused by the interaction between the resistor body and the encapsulant, which resulted in this asymmetry to strain distribution within the joint structure.

Similar diagrams are shown in Fig. 6B, C representing transportation and handling segment #2 as well as the use segment, respectively. In Fig. 6B, a reduced, maximum TMF strain value of 0.017 is observed vs. 0.021 for segment #1 in Fig. 6A because of the smaller ΔT in the #2 condition. This trend continues with Fig. 6C where a smaller ΔT of the use segment caused a nearly order of magnitude smaller strain maximum when compared to either transportation and handling segment. Therefore, ΔT has a larger effect than a considerably longer cycle duration of one year vs. 10 h for the former segments.

The diagram in Fig. 6D shows 100% cracking due to the use segment. The

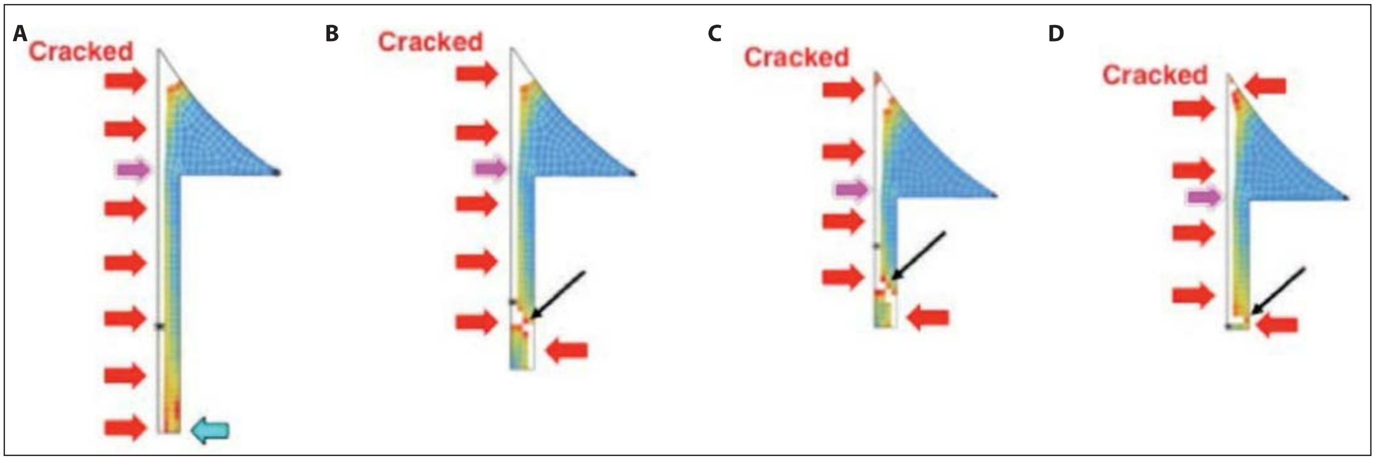

Fig. 8 — Computational models generated the 100% crack situation for these hole fill conditions: A — 100%; B — 75%; C — 50%. D — The 100% crack morphology is shown for the case of 50% hole fill and the absence of encapsulant under the PWB. The computations were based on the use segment (16°C/33°C; 1 cycle/year). The magenta arrow is the site of maximum strain. The cyan arrow in A signifies the bottom terminus of the joint. The black arrow in B –D indicates the location where the primary crack and the second crack, which originated from the bottom, joined together.

crack is represented by the white segment alongside the red arrows. The initiation point was at the magenta arrow. The crack grew in two directions, toward the top of the fillet as well as to the bottom terminus. The crack path was entirely along the pin/solder interface.

The fatigue strain contour diagrams shown in Fig. 7 represent the hole-fill variants exposed to, in this case, a single use segment (16°C/33°C; 1 cycle/year). Similar trends were observed as were noted for the two transportation and handling segments. The TMF strain values increased approximately 10% between hole fill conditions from 100% (Fig. 7A) to 50% (Fig. 7C), but then increased by 57% from the case shown in Fig. 7C to the configuration whereby encapsulant was removed from underneath the bottom PWB (Fig. 7D). Yet the location of highest strain (magenta arrows) remained unchanged between all four cases. In fact, the location and magnitude of strain in Fig. 7A were identical to those parameters in Fig. 6C (baseline), which reinforces the earlier observation that the presence of the bottom fillet had limited impact on the fatigue life of the solder joint in the presence of the encapsulant.

Decreasing hole fill caused a marked increase in TMF strain at the bottom terminus of the joints (cyan arrows). This enhanced strain remained less than that at the crack initiation point (magenta arrows), including Fig. 7D. However, those cyclic strains would also be imparted on the Cu barrel of the PWB through hole and potentially cause an electrical open by fatigue of the Cu before a 100% crack has propagated through the solder (Ref. 3).

The finite element models are shown in Fig. 8 that represent the 100% crack path in each of the four configurations. Figure 8A shows the 100% crack had propagated in opposing directions from the location of maximum strain (magenta arrow). The cracks followed the solder/pin interface to the top of the fillet and to the bottom terminus (cyan arrow). A small, localized strain at the latter location was insufficient to deviate the crack from that path.

The 100% crack path is shown in Fig. 8B, C for the cases of 75% and 50% hole fill, respectively. The predominant crack path remained at the solder/pin interface. However, the localized strain at the bottom terminus increased in magnitude to the extent that it generated a second crack at the solder/Cu barrel interface. The crack then joined up with the primary crack at the locations denoted by the black arrow. The number of cycles to 100% cracking reflects the combined contributions of the two cracks.

Lastly, the 100% crack diagram in Fig. 8D shows nearly the same crack morphology as that presented in Fig. 8C. The secondary crack joined the primary crack closer to the terminus. Therefore, the absence of encapsulant affected propagation of the primary crack along the solder/pin interface more so than it impacted the second crack that originated from the bottom terminus.

Conclusions

1. A computational model was used to predict the thermal mechanical fatigue (TMF) of through-hole solder joints that are partially filled with 63Sn-37Pb solder.

2. The model predictions addressed a sequence of multiple environments that encompassed handling, transportation, and use segments within the assembly lifetime.

3. There were two failure criteria: a) cycles to reach TMF crack initiation, and b) cycles to cause a 100% cracking of the joint that leads to an electrical failure.

4. The TMF lifetime used up in the service environment (two transportation segments and the use segment) was less than 1% for the more conservative crack initiation criterion. An absence of encapsulant from under the PWB caused a 3.9% loss of fatigue life.

5. Although the fatigue strains increased at the bottom terminus with decreasing hole fill, they did not significantly affect the TMF failure of the

solder joint. However, those cyclic strains were capable of causing fatigue damage to the Cu barrel of the PWB hole.

6. Three high-level findings were obtained: a) TMF deformation, which leads to crack initiation, does not scale the same as the cracking process; b) incomplete encapsulation accelerates the TMF of through-hole interconnections; and c) transportation and handling procedures can generate a greater degree of TMF damage than does actual the use segment. WJ

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P. T. VIANCO (ptvianc@sandia.gov) *and M. K. NEILSEN are with Sandia National Laboratories, Albuquerque, N.Mex.*

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