Fatigue Life Estimation of Surface Mount Solder Joints

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Abstract—A novel and direct method to measure the stress-strain properties of surface mount solder joints is proposed in this paper. The specimen used in the experiments is a quad flat pack (QFP)-solder-printed circuit board (PCB) assembly and the fabrication of solder joints makes use of conventional surface mount technology (SMT). Mechanical cycling and thermal shock testing can be conducted directly on the specimen after assembly. In this manner, the specimen represents practical SMT solder joints in electronic products as far as possible. It is shown that the joint strain and stiffness of chip modules are good evaluation indices to reveal the fatigue status of solder joints. It is further proposed that the criterion of 50% load drop should be used for defining the fatigue life of solder joints. Finally, it is recommended that the total displacement $\Delta$$a_2$ be used to measure the strain-fatigue life relation for both leaded and leadless joints.

Index Terms—Surface mount technology, fatigue life, solder joint.

I. INTRODUCTION

SURFACE MOUNT technology (SMT) is widely used in electronic products. The reliability of surface mount solder joints, therefore, has drawn a lot of attention from researchers as well as manufacturers. One of the major problems is fatigue failure arising primarily from the imposition of mechanical strain in service. The strain is generated from the temperature fluctuations and thermal expansion mismatch between the printed circuit board (PCB) and components or chips. Thermal fluctuations arise due to environmental temperature changes, and power cycling of devices. Therefore, thermal strain may recur again and again.

Much work has been done on the fatigue mechanism of bulk solders [1], [4] and solder joints [5], [6]. Some attempts have quantitatively correlated the fatigue life with the strain. However, as a real SMT solder joint consists of many parts and the service conditions are changeable, the fatigue life of solder joints cannot be predicted directly. Moreover, some contradicting results may be obtained from different testing methods. Hence, the details of a test method are important. The more accurately a test method can emulate practical situations, the more reliable would be the result.

This paper presents a new and direct approach to measuring the fatigue properties of surface mount solder joints. The method employs a specimen whose materials and manufacturing processes were identical to that of a practical electronic assembly. In this manner, it is possible to gain significant information on the fatigue life of a practical solder joint.

II. PREVIOUS WORK

A review of the methods employed in the current fatigue life study of solder joints is helpful. Briefly, the previous work can be summarized into two parts.

A. Specimen Design

The specimen design is the first important aspect at a test method. Specimens currently used to test the fatigue life of solder joints can be divided into three categories as
1) bulk solder [1], [3], [7];
2) simplified shear samples [2], [8]-[12]; and
3) SMT solder joints [6], [13]-[16].

Bulk solder samples that are entirely made up of solders give consolidated data on the fatigue properties of the solders, including the microstructure evolution under different thermal conditions. However, bulk samples do not behave the same as solder joints. A simplified shear joint is usually fabricated from two or three pieces of plates joined by solder and often called a single or double shear specimen, as seen in Fig. 1(a)-(c). The ring-pin type [Fig. 1(d)] is also a simplified shear specimen. The plate or bean materials chosen in the shear samples are mostly copper or other metals. The simplified shear specimens produce systematic data for the correlation of the fatigue life with joint strain. Since a pure shear strain can be obtained except in the case of a single shear specimen, such results on fatigue studies should be more reliable and repeatable. These results, together with that of bulk samples, have provided a firm basis for further fatigue studies. For example, how to make use of the findings to measure or predict the fatigue life of a real SMT solder joint? Fatigue prediction and testing for SMT solder joints is considerably complicated due to the facts that their structure, material, and preparation conditions are quite different to that of the bulk solder or simplified solder joints.

Prear [13], [14] employed fiberglass-impregnated epoxy as the plate material in the double-shear specimen, which is...
Load

Fatigue life is determined by a load drop $\Phi$ in the hysteresis loop

$$\Phi = 1 - \Delta P/\Delta P_1$$  \hspace{1cm} (1)

where $\Delta P$ and $\Delta P_1$ are the total load ranges at a given cycle and at the first cycle, respectively. Therefore, the fatigue life is defined as the number of cycles required to reach a given value of $\Phi$, which is denoted by $N_\Phi$.

A traditional equation to correlate strain with fatigue life is given by Coffin–Manson’s equation

$$\Delta \varepsilon_p = C N_\Phi b$$  \hspace{1cm} (2)

where $\Delta \varepsilon_p$ is the applied plastic strain and may be substituted by the total strain $\Delta \varepsilon_t$ [11]. Many researchers adopt the criterion of 50% load drop as a practical means to define fatigue life [9], [18]. This is regarded as a conservative prediction because the solder joint may not be electrically or physically split after $N_\Phi$ cycles.

### III. Experimental Design and Procedure

The experimental set-up is schematically shown in Fig. 2. The specimen is composed of a PCB and a quad flat pack (QFP) chip joined together by means of solder, very similar to a normal SMT assembly. Strain gauge extensometers are located at $\delta_{2p}$, $\delta_C$ and $\delta_a$. Fig. 2(c) shows an extensometer for measuring $\delta_{2p}$. The extensometer can be placed at any point between point $d$ and the centre of the PCB. When measuring $\delta_C$, the extensometer is attached to the component leads (point $a$) of the QFP chip as shown. Usually, only one extensometer was used for measuring $\delta_{2p}$ during strain cycling tests. Each knife edge of the extensometer was clamped by a plastic ring and no slippage was observed during testing. The basic correlation between these displacements and the joint strain are as follows:

$$\Delta \delta_f = y_b - y_a$$  \hspace{1cm} (3)

$$\Delta \delta_f = (\Delta \delta_{2p} - \Delta \delta_C)/2$$  \hspace{1cm} (4)

$$\Delta \delta_f = \Delta \delta_a - \Delta \delta_p$$  \hspace{1cm} (5)

$$\Delta \varepsilon_f = \Delta \delta_f/(2h)$$  \hspace{1cm} (6)

$$\Delta \varepsilon_{2p} = \Delta \delta_{2p}/\delta_{2p}$$  \hspace{1cm} (7)

where

- $\Delta \delta_f$: Displacement across the solder joint.
- $y_a$: Coordinate of the point, $a$, at the maximum tensile load.
- $y_b$: Coordinate of the point, $b$, at the maximum tensile load.
- $\delta_{2p}$: Length of extensometer gauge across two split PCB’s.
- $\Delta \delta_{2p}$: Total displacement between two split PCB’s.
- $\Delta \delta_C$: Displacement of chip.
- $h$: Thickness of the solder joint.
- $\Delta \delta_a$: Displacement across the solder joint and PCB.
- $\Delta \delta_p$: Displacement in a single PCB.
- $\Delta \varepsilon_f$: Total shear strain of the solder joint.
- $\Delta \varepsilon_{2p}$: Corresponding strain to the displacement, $\Delta \delta_{2p}$. The solder joint of “two-chips-on-one-substrate” was studied. Nir et al. [15] obtained a useful correlation between the shear strain and fatigue life. However, since both the chip and substrate were made from silicon, it was not suitable for thermal cycling test. Solomon [18] measured the hysteresis loops of leaded and leadless chip solder joints and showed the relation between displacement, load drop, and fatigue life. There was a difference to a realistic SMT solder joint. A slot was cut in the PCB underneath the chip carrier after assembling in the test grips. Therefore, this method of measuring the shear strain or stress of SMT solder joints was more applicable to practical SMT assembly.

### B. Fatigue Life Prediction

A good method should accurately determine the fatigue life or the number of cycles to failure. Electrical resistance measurement or continuity monitoring was recommended as a feasible detection method for the failure of solder joints [13]. Good progress on electrical resistance measuring techniques has been made [19], [20]. The electrical detection of failures is possible but practically difficult. The electrical continuity is instantaneously lost after the formation of a crack throughout the joint, but soon afterwards the entire specimen is electrically conductive due to physical contact. The relationship between fatigue failure and resistance change has not been established systematically. Visual inspection is also found to be unsuitable because the cracks in a solder joint cannot be detected quantitatively within a reasonable amount of time. The most common method is the stress–strain cycling test, in which the
The above equations have neglected the bending of the PCB during testing. The joint length is very small, and it is difficult to measure $\Delta \delta_J$ directly. However, from (4) and (5), $\Delta \delta_J$ can be obtained indirectly through measuring $\Delta \delta_a$ and $\Delta \delta_p$, (in mm) or measuring $\Delta \delta_{2p}$ and $\Delta \delta_C$. For a relatively low force, the displacement of a single PCB, $\Delta \delta_p$, is given by the following equation:

$$\Delta \delta_p = \frac{PL}{E_p A}$$  \hspace{1cm} (8)

where $E_p$ is the Young’s modular of the PCB, and $L$ and $A$ are the length and cross section area of the PCB, respectively. The PCB has dimensions of 70 mm $\times$ 16 mm $\times$ 1.48 mm and is made from fiber reinforced epoxy-glass (FR-4) with $E_p = 11 \times 10^9$ N/mm$^2$. $P$ is the total applied load and is usually of the order $P \leq 100$ N. For $P = 100$ N and substituting the parameters into (8), $\Delta \delta_p$ is calculated to be equal to about $6 \times 10^{-9}$ mm, which is very small and can be neglected as compared with $\Delta \delta_a$. Hence, (5) becomes

$$\Delta \delta_J \approx \Delta \delta_a.$$  \hspace{1cm} (9)

Equation (9) shows that the joint strain can be measured through measuring $\Delta \delta_a$. The gauge length of the extensometer is 12.5 mm for measuring $\Delta \delta_a$ and $\Delta \delta_{2p}$ and 25 mm for measuring $\Delta \delta_C$. For a larger module, a longer extensometer is needed.

During thermal expansion, if the displacement in the unsplit PCB is equal to $\Delta \delta_{2p}$, the split PCB assembly subjected to mechanical cycling is able to simulate the unsplit PCB assembly subjected to thermal cycling. This will be discussed further in the Appendix. The equivalent thermal strain can be calculated using (6). Hence, $\Delta \delta_{2p}$ is very useful in correlating the thermal strain with mechanical strain.

Components chosen were standard plastic QFP-44 and QFP-80. In the experiments, only the leads of two opposite sides were soldered in order to minimize the variables. The lead material was kovar alloy. The solder paste used was Sn62-Pb38 RM92 (no-clean). Solder pastes were stencil printed on the PCB by screen printer (HTI-SMT). The thickness of solder paste was 0.2 ± 0.05 mm. Components were put on the PCB by a semiautomatic pick-and-place machine. The specimen was reflowed inside a three-zone infrared oven (PRECISOLD PS-3000) at 210 °C with a dwell time of 70 s. Thermal shock testing was performed in a TABAI TSA-70L air to air thermal shock chamber. The thermal cycling range is from $-35$ °C to $125$ °C. The holding time was 15 min and 20 min. The ramp time for both heating and cooling was less than one minute.

The PCB was cut in half with a gap width of 2 mm along the longitudinal direction after all the thermal tests (or other life experiments in which failure monitoring is difficult) were completed. Then the PCB assembly was made into a shear specimen for mechanical tensile and strain cycling testing. The fatigue life of virgin parts can be recorded accurately by this way. Furthermore, with correlating thermal to mechanical cycles by using only strain, the previous life experiment can be performed accurately and easily. This method of testing can be called the direct strain measurement (DSM), as the mechanical strain is applied to the solder joints directly. In the work described earlier [18], the solder joints are first formed and the slot is already in place during thermal cycling tests. This is the main difference with the DSM technique employed in this work. The presence of a slot in the PCB can greatly affect the thermal expansion and the stress distribution during reflow and thermal cycling, especially in the latter case, because of CTE mismatch between the PCB and the chip. Thermal fatigue life is affected. In addition, the slot may also affect the heat sink during thermal cycling. Consequently, the fatigue life of solder
joints will certainly be modified by the presence of a slot in the PCB assembly. Thus, the specimen should not be slotted in order to simulate a practical SMT product. More importantly, the DSM results are applicable directly to practical SMT solder joints since the specimen is not required to have a slot in the PCB. After thermal cycling, the practical PCB assembly can be made to form shear specimens by proper cutting. Then a lot of mechanical testing including strain cycling and creep can be done on the practical SMT solder joints directly. While cutting, much care was taken to ensure no damage to the component and the leads.

Mechanical strain or stress cycling was performed using an INSTRON 4206 universal machine. It was conducted at room temperature and without dwell time at peak loads. The cycling was restrained at a low compressive displacement because a big compression force might cause severe bending of the PCB. Therefore, the cycling could be under asymmetrical loading or displacement. Typical hysteresis loops of a mechanical strained joint system (QFP chip-solder-PCB) are shown in Fig. 3. The strain cycling was run on QFP-44 solder joints from $-0.135$ mm to $+0.2$ mm. As seen from Fig. 3, well-behaved hysteresis loops with different elastic and plastic displacements have been generated. The loops tilt and become narrow as the number of strain cycles increases.

IV. RESULTS AND DISCUSSIONS

A. Strain and Stiffness Development During Mechanical Stress Cycling

The displacement of a compliant leaded chip, $\Delta \delta_C$, is related to the applied load by a factor $K$ as

$$K = \frac{P}{\Delta \delta_C}. \quad (10)$$

Substituting (10) into (6), then

$$\Delta \varepsilon_J = \frac{(\Delta \delta_{2p} - P/K)}{(2h)}. \quad (11)$$

It should be noted that the index $K$ represents the stiffness of the module including leads and may vary. Its value may be calculated from the finite-element method (FEM). For QFP gull-wing solder joints, the variables $\Delta \varepsilon_J, \Delta \delta_{2p}$ and $P$ can be measured experimentally and, hence, the stiffness coefficient $K$ may be determined from (11). For J-leaded and leadless solder joints, $\Delta \varepsilon_J$ cannot be obtained directly through measuring $\Delta \delta_{2p}$. In that case, it can be obtained from (11) by measuring $\Delta \delta_{2p}$ and $P$ if $K$ is known.

Fig. 4 shows the variations of strains $\Delta \varepsilon_J, \Delta \varepsilon_{2p}$, and stiffness $K$ of a QFP-44 gull-wing solder joint system during stress cycling. The applied load amplitude was 0.066 kN and remained constant during cycling. As the number of stress cycles increases, $\Delta \varepsilon_J$ and $\Delta \varepsilon_{2p}$ increase gradually while $K$ decreases. This shows that both the solder joints and
leads yield smoothly during stress cycling. However, both the stiffness \( K \) and the strain \( \Delta \varepsilon_{\text{J}} \) showed an abrupt change at about 2230 cycles, indicating the beginning of fatigue failure. The solder joint system failed soon after the point. Four solder joints were found to be fractured at 2520 cycles. At the same time, seven leads were also found to be fractured. The fractograph in Fig. 5(a) clearly shows the occurrence of fracture at both leads and solder joints. There were also some cracks seen at the root of remaining leads of good solder joints. Fig. 5(b) shows the X-ray radiograph of the same joints of Fig. 5(a). Many pores were observed in the fractured solder joints in both Fig. 5(a) and (b). The diameters of big pores are greater than 0.1 mm. However, few pores appeared in unfractured solder joints as shown in the X-ray radiograph of Fig. 5(b). This confirms that the existence of pores in solder joints may well be a major cause of joint failure.

Similar results were obtained from a QFP-80 solder joint system. In Fig. 6, each specimen consists of 24 lead pairs. Tensile forces were applied along the longitudinal direction where the thermal expansion was greater. During cycling, the total applied strain was 3.2% and was kept constant throughout. Up to about 530 strain cycles, the index \( K \) changed slowly and the joint strain \( \Delta \varepsilon_{\text{J}} \) and \( P/K \) were fairly constant. After that, \( K \) decreased sharply while the joint strain increased drastically. This suggests that fatigue occurred both at the leads and solder portion. Six solder joints were found to be fractured at the solder portion, thus leaving the leads freely movable. Three leads had cracks and the other joints had no obvious damage. Hence, the variations of \( K \) and \( \Delta \varepsilon_{\text{J}} \) can be used to determine whether the failure of leads or solder joints has occurred. As the joint strain \( \Delta \varepsilon_{\text{J}} \) is fixed during the cycling (controlled by \( \Delta \varepsilon_{\text{J}} \)), it is possible to determine the relationship between the joint strain and the number of cycles to failure by simply measuring \( \Delta \varepsilon_{\text{J}} \). It is also noted that values of \( K \) for QFP-80 were much smaller than those of QFP-44 due to the fact that the leads' height of QFP-80 was greater than that of QFP-44. Therefore, QFP-80 leads were more compliant and could sustain a higher strain as compared with QFP-44. The experimental results in Figs. 4 and 6 confirm the observation that both the leads and solder have developed a fatigue problem during mechanical cycling and the leads of QFP-44 and QFP-80 chips can exhibit fatigue at a relatively high stress or strain.

B. Fatigue Properties of Practical QFP-80 Joints

In order to understand fatigue behavior in a practical solder joint, a QFP-80 chip assembly was taken from a used hand phone as shown in Fig. 7. The chip was a UNIDEN UC1193 and the phone was assembled in 1990. To examine the effects of thermal cycling on the joint strain and index \( K \), QFP-44 solder joints were thermally cycled between \(-35 \, ^\circ\text{C}\) to \(125 \, ^\circ\text{C}\) for 1000 cycles before mechanical strain testing. Strain \( \Delta \varepsilon_{\text{J}} \), \( \Delta \varepsilon_{\text{J}} \) and index \( K \) of different QFP solder joints were
taken from a certain cycle in the mechanical cycling with a total applied load of 66 N. Results are plotted in Fig. 8. The joint strain of thermally cycled solder joint almost had no change as compared with the original one. The joint strain after mechanical cycling for 1000 cycles has increased from 5.8% to 6.8%. The index K decreases after both the mechanical cycling and thermal cycling tests, while the mechanical cycling causes more decrease in K value. This shows that the mechanical cycling had a greater effect on the strain and stiffness K than the thermal cycling. The main reason is that the applied thermal strain was much smaller than the mechanical strain. The total joint strain in the thermal cycling was 0.69% (see Table I), roughly 10% of that in the mechanical cycling. The other explanation is that eutectic Sn–Pb solder has a low melting point and becomes more pliable at high temperature.

Fig. 8 also shows that in order to get the same joint strain, a larger strain, \( \Delta \varepsilon_{2p} \), is required by a QFP-80 solder joint than a QFP-44 one. This indicates that QFP-80 solder joints could sustain a higher thermal expansion strain due to the low stiffness of its leads. In addition, both the strains \( \Delta \varepsilon_{2p} \) and \( \Delta \varepsilon_{j} \) in the used QFP-80 chip joints increased markedly, whereas the stiffness K almost had no change in contrast to the newly made QFP-80 chip joints. This simply confirms that the solder joints in the used QFP-80 exhibited fatigue earlier than the leads as indicated by the load–strain cycling curve in Fig. 9. The load of solder joints for the used chip dropped about 30% at the first cycle as compared with that of a newly made one, suggesting that the solder of the hand phone joints had accumulated a certain fatigue before this test. This is demonstrated by the values of stiffness K and joint strain at the first cycle in Fig. 8. Fatigue was seen in the joints of the used hand phone at about 750 cycles, whereas for the newly made joints at around 1050 cycles. The fatigue load of the used hand phone joints was 0.035 kN, approximately half of the maximum load for the newly made joints (at the first cycle). However, the newly made joints showed fatigue much earlier, before the cycle of 50% load drop. This is because fatigue occurred at the leads. Furthermore, all the leads in the newly made joints were found to fracture at the end of the cycling test. The solder could sustain a higher number of strain cycles before its failure provided that the leads remained in good conditions. On the other hand, the load of the joints in the used hand phone dropped gradually until the final fracture occurred at the solder. This indicates that the solder joints in the used hand phone have sustained a high number of cycles and low strain fatigue history. This corresponds roughly to 1000 cycles at a total displacement of 0.462 mm.

C. Fatigue Life Determined by \( \Delta \delta_{2p} \) and \( \Delta \varepsilon_{2p} \)

As evident from the above discussion, the displacement \( \Delta \delta_{2p} \) should provide a useful means for measuring the fatigue of solder joints. In practical service, however, solder joints exhibit fractures mostly at the solder portion but not at the leads. This behavior should be reflected by the DSM. As discovered from the above experiments, this may be achieved by decreasing applied load or strain during cycling test. This method would be the most accurate, but a very large number of strain cycles is usually required to arrive at the fatigue point. A simpler method is to increase the joint stress which is equal to the applied load divided by the joint area. This can be done by decreasing the area of the solder joints while keeping the load constant. There exists a critical point for stress dropping. For all applied total displacements, the critical point was at 50% stress drop. The solder joint begins to show failure beyond that point. Therefore, a 50% load drop is a useful criterion to define joint failure, in good agreement with other experimental results [18]. It is also found that the joints were fractured mostly at the solder portion, although some leads were fractured at the displacement of 0.388 mm.

Fig. 11 shows the fatigue life as a function of the applied displacement \( \Delta \delta_{2p} \), which is plotted as several straight lines in the log–log chart. For a 50% stress failure definition, the correlation between the displacement \( \Delta \delta_{2p} \) and the number of cycles to failure \( N_f \) can be approximated by following empirical equation:

\[
\Delta \delta_{2p} = 0.99N_f^{-0.26} \text{ (mm).} \quad (12)
\]

Equation (12) has a correlation coefficient of 0.986 and is reasonably accurate in use. Fig. 12 shows a plot of the
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TABLE I

<table>
<thead>
<tr>
<th>No</th>
<th>Researchers</th>
<th>Specimen</th>
<th>Solder</th>
<th>Strain (frequency temperature).</th>
<th>Δε_J = CN_f^b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>This study</td>
<td>QFP-44/PCb</td>
<td>Sn62/Pb38</td>
<td>0.14 Hz 25 °C</td>
<td>2.57 -0.61</td>
</tr>
<tr>
<td>2</td>
<td>Solomon</td>
<td>QFP-64/PCb</td>
<td>Sn63/Pb37</td>
<td>0.33 Hz 35 °C</td>
<td>N/A N/A</td>
</tr>
<tr>
<td>3</td>
<td>Solomon</td>
<td>single</td>
<td>Sn60/Pb40</td>
<td>0.2 Hz -50 °C 150 °C</td>
<td>1.14 -0.51</td>
</tr>
</tbody>
</table>

Solomon [6] as follows:

\[ \Delta \varepsilon_J = 1.14 N_f^{-0.51} \]  \( (13) \)

Fig. 12 shows the variations of fatigue life with joint strain obtained by the DSM method. The theoretical prediction from (13) is also plotted in the same figure for comparison. From that, it can be seen that the joint strain obtained by the DSM test is close to that of Solomon [6] even though it is a little higher for the case of lower fatigue life. The difference is mainly due to the fact that the strain in the DSM test is the total strain and should be larger than the plastic strain by about 10% [11]. The other likely reason could be the lower cycling frequency adopted in this work than that of Solomon [6]. In summary, \( \Delta \delta_{2p} \) can be regarded as a controlled strain in the DSM fatigue test, generally applicable to many types of surface mount solder joints. Equation (6) is useful to correlate the joint strain with the controlled strain. In this manner, the number of cycles to failure in the fatigue test may be associated with the joint strain through the Coffin–Manson’s Equation (13).

Thermal strain can be conveniently applied to a joint during thermal shock testing or thermal cycling. Combining mechanical and thermal cycling is a good way to do fatigue testing. The damage model for combined thermal and mechanical cycling may be expressed in the following modified form:

\[ \left( \frac{n_t}{N_t} \right)^{C_t} + \frac{n_m}{N_m} = 1 \]  \( (14) \)

where \( n_t \) is the number of cycles conducted, \( N_t \) is the number of cycles to failure under single type of strain cycling, subscripts \( t \) and \( m \) represent thermal cycling and mechanical cycling, respectively, and \( C_t \) is a coefficient to correlate the fatigue damage between mechanical and thermal cycling. It is noted that \( n_m \) is the number of remaining mechanical cycles to failure after \( n_t \) thermal cycles have been exercised on the solder joints. Normally, \( N_t \) and \( N_m \) are constant if the joint dimensions and strain cycling conditions are unchanged. Since \( n_m \) is easily measured by direct measurement, \( n_t \) can be assigned to any value from 0 to \( N_t \). Therefore, the fatigue damage can be determined through measuring \( n_m \).

The experimental results are summarized in Table II and the number of predicted remaining cycles to failure \( (n_m) \) are also plotted in Fig. 13. As seen from Fig. 13(a) and (b), the number

experimental results versus the theoretical prediction from (12), and compares with the data of Solomon [18]. The experimental conditions are listed in Table I. Fig. 12 shows that the results obtained by Solomon are in good agreement with the experimental data of this work as well as with (12). This is because the specimens and strain cycling conditions adopted in this work are similar to those of Solomon’s. The stiffness constant \( (K) \) of QFP-44 is close to that of QFP-64, as they have a similar configuration. The slot in the PCB has a negligible effect on the fatigue life provided that only the isothermal cycling test is performed on the specimen. It should be noted that \( \Delta \delta_{2p} \) is the total displacement resulting from the chip, solder joints, and PCB. In order to make comparison between different specimens and joint configurations, one should use \( \Delta \varepsilon_J \) to correlate the fatigue life as in Coffin–Manson’s equation. When estimating the fatigue of eutectic lead–tin solder, the most common empirical equation is obtained by

![Graph](image-url)
Fig. 12. Comparison of the fatigue lives at 50% load drop obtained from the DSM with data from Solomon (1992).

Fig. 13. Fatigue lives of solder joints under both thermal cycling and mechanical strain cycling in shear specimen (a) and QFP-44 joints (b).

Fig. 14. Thermal strain calculations of QFP-44/PCB assembly.

V. CONCLUSION

From a systematic and experimental investigation of the stress–strain properties of surface mount solder joints fabricated from a conventional reflow process, the following conclusions can be drawn:

1) The DSM developed in this work is found to be useful in practice and should provide a novel and direct technique to measure stress–strain properties of SMT solder joints. It is of practical use in predicting the fatigue life of a real
The specimen does not initially have a slot and can simulate a practical PCB assembly to the greatest degree of accuracy.

2) The stiffness index $K$ and $\Delta \delta_J$ or $\Delta \delta_{2p}$ are good indicators to show the fatigue status of solder joints. When $\Delta \delta_J$ increases, the solder joints develop fatigue. When $K$ decreases, the chip leads develop fatigue. When $\Delta \delta_{2p}$ increases, the leaded solder joint system including both the solder joints and leads develop fatigue.

3) QFP-80 has lower lead stiffness than QFP-44, and therefore may sustain a higher mechanical or thermal strain for the same fatigue lifetime.

4) The measurement of total displacement $\Delta \delta_{2p}$ can be recommended as a practical technique to estimate the fatigue life during strain cycling tests for both leaded and leadless solder joints. The equation $\Delta \varepsilon_J = \frac{(\Delta \delta_{2p} - P/K)(2h)}{(2L_c)}$ is used to correlate the total displacement with the joint strain. The correlation between the joint strain and fatigue life for QFP lead joints, as measured by this work, is in good agreement with the Coffin-Manson’s equation.

### APPENDIX

**Analysis of Thermal Strain in Slotted and Split PCB Assemblies**

As described earlier in this paper, during thermal cycling $\Delta \delta_{2p}$ and $\Delta \delta_C$ can represent the total thermal displacements of the whole PCB and chip, respectively. For a uniform rise of temperature $\Delta T (\Delta T \geq 0)$, if the displacements are unrestricted it follows that

$$\Delta \delta_{2p} = \alpha_p L_C \Delta T$$  \hspace{1cm} (A1)

and

$$\Delta \delta_C = \alpha_C L_m \Delta T + \alpha_l (L_C - L_m) \Delta T$$  \hspace{1cm} (A2)

where $\alpha_p$, $\alpha_C$, and $\alpha_l$ are the coefficients of thermal expansion (CTE’s) of the PCB, chip, and lead, respectively. $L_C$ is the distance between two opposite pairs of solder joints, and $L_m$ is the length of the chip module. As shown in Fig. 14, the PCB has only a slot with a width of $s$ and a length less than the width of the chip module. The thermal strain in the solder joints of the unslotted (or normal) PCB assembly at the longitudinal direction can be determined by (6). This is because the elastic strains are negligible [see (8)]. For the slotted PCB assembly in Fig. 14, the thermal displacement of the slotted part should be deducted. The joint strain in the slotted PCB assembly is thus

$$\Delta \varepsilon_{J, \text{slit}} = \Delta \varepsilon_J - \alpha_p s \Delta T.$$  \hspace{1cm} (A3)

If the length of the slot is great enough so that the PCB can be considered to be split completely into two equal PCB’s, then the PCB will expand independently during thermal cycling. In Fig 14, a small PCB will expand from its own central line. The direction of the expansion is opposite to that of the $\Delta \delta_C$. Then the correspondent joint strain is

$$\Delta \varepsilon_{J, \text{split}} = \frac{(\Delta \delta_j + \Delta \delta_C)}{(2h)}$$  \hspace{1cm} (A4)

and

$$\Delta \delta_p = \alpha_p \frac{(L_p + s)/4 - L_C/2\Delta T/h}{L_c}$$  \hspace{1cm} (A5)

where $L_p$ is the length of the whole unsplit PCB. Normally, $\Delta \varepsilon_{J, \text{split}}$ is greater than $\Delta \varepsilon_{J, \text{split}}$ and can be the maximum value of the joint strain in the slotted PCB assembly. An example is shown in Table II for calculating the joint strain in different cases of PCB assembly, assuming that the QFP-44 solder joints with a slot of 3 mm went under thermal cycling by $\Delta T = 160 ^\circ C$ (from $-35 ^\circ C$ to $125 ^\circ C$). It is learned from Table II that the joint strain in the slotted PCB assembly is dependent on the materials of both the chip and the PCB. For the plastic chip chosen in this work, the joint strain in the slotted PCB assembly varies from 1.59% to 16.9%. This is much greater than the joint strain in the unslotted PCB assembly (0.69%). For a ceramic chip, it varies from 6.23% to 9.16% and may be equal to the joint strain in the unslotted PCB assembly in special cases. Therefore, the slotted specimen cannot simulate the normal specimen in thermal cycling tests.

### REFERENCES


D. J. Xie, for a photograph and biography, see p. 153 of the February 1996 issue of this TRANSACTIONS.

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