Abstract—A mechanical approach employing cyclic twisting deformation to a surface mount assembly is examined as an alternative to temperature cycling for evaluating solder joints fatigue performance. This highly accelerated test is aimed at reducing solder joint reliability testing cycle time. In this study, the mechanics of solder joints in a surface mount assembly subjected to cyclic twisting deformation is investigated. For this purpose, a test package with 24 by 24 peripheral-array solder joints is modeled using the finite element method. Unified inelastic strain theory defines the strain-rate-dependent plastic stress-strain response of the 60 Sn–40 Pb solder. Cyclic twisting deformation in the range of $±15^\circ$ per $50$ mm length of the assembly board at a rate of $120$ s per twist cycle was applied. The calculated stress and strain distributions in the critical solder joint are compared with those predicted for temperature cycling and accelerated temperature cycling tests. Results showed that the accumulated inelastic strain concentrates in a small region of the critical solder joint near the component side for temperature cycling and near the board side for cyclic twisting load cases. The rate of inelastic strain accumulation per fatigue cycle in the solder joint for both temperature cycling (TC1) and mechanical twisting (MT1) tests are similar. Thus, mechanical twisting test imparts similar deformation characteristics to temperature cycling tests in terms of the shear strain range. Low cycle fatigue is dominated by localized shear effect as reflected in the largest shear strain range of the hysteresis loops. The Coffin–Manson strain-based model yielded more conservative prediction of fatigue lives of solder joints when compared to energy-based approach.

Index Terms—Finite element analysis (FEA), low cycle fatigue, mechanical cyclic twisting (MT1), reliability, temperature cycle (TC1).

I. INTRODUCTION

The competitive nature of electronic packaging industry calls for a faster method of reliability assessment to meet the fast pace of product development cycle. In this respect, accelerated temperature cycling tests and mechanical cycling tests have been evaluated as an effective acceleration technique to thermal cycling [1]–[4]. Temperature cycling of solder assemblies in an environmental chamber is intended to duplicate the characteristics of the actual stress factors experienced by the assembly during processing, reliability testing and service. These include temperature and humidity, shock and vibration, thermal or power cycles. Accelerated temperature cycling profile consists of thermal shock cycles or introduces dwell time period at peak temperature levels. The resulting cyclic stresses and strains induced low cycle fatigue damage in the solder alloy [5]–[8].

Mechanical cyclic load test is capable of accelerating the failure by fatigue of solder joint. Fatigue failure occurs by initiation and slow propagation of a crack to a critical length prior to final fracture of the solder joint. Bending tests are useful for evaluating board level assemblies for performance under mechanical stresses. Three- and four-point bend tests have been used to simulate manufacturing, handling, shipping and network conditions of surface mount assemblies and for evaluating mechanical reliability of chip scale packages [2], [4], [9]–[12]. Several packages can be tested at multiple load levels with a single three-point bend test. A direct strain measurement method was used for peripheral leaded device where mechanical strain is induced by the application of axial cyclic loading [13]. Torsion test imparts cyclic twisting deformation on an assembled PCB to mimic solder joint fatigue failure mechanisms as observed in temperature cycling tests. Due to twisting load on area array solder joints, diagonal solder joints experience higher strains similar to that observed in a package subjected to thermal load [3].

Finite element analyses (FEAs) have been employed extensively to evaluate fatigue performance and reliability of solder joints in surface mount assemblies [6], [7], [12]. FEA simulations are able to provide insights on low cycle fatigue failure mechanism of solder joint. Its success lies in appropriate representation of the assembly, boundary conditions, applied loads and accurate material model. This study examines solder joint fatigue in a surface-mount test assembly under cyclic twisting deformation. Evolution characteristics of inelastic strains in critical solder joint under temperature cycling (TC1), accelerated temperature cycling by dwell time period (TD1) and mechanical twisting cycles (MT1) are compared in view of validating the accelerated life techniques. Fatigue life prediction models based on strain range [14], [15], and energy density [16] are used to estimate fatigue life of these solder joints.

II. FINITE ELEMENT PROCEDURES

A surface-mount test assembly with a peripheral array of 92 solder joints, Si-die, FR-4 substrate, Cu$_6$Sn$_5$ intermetallics and layers of copper traces is modeled, as illustrated in Fig. 1(a) for use in temperature cycling cases. In mechanical twisting cases, a full (global) model is subjected to a prescribed twist deformation at the rigid grip ends of the assembly. This full model simulation established the deformation field and identified the location of critical solder joints. Due to symmetry
of the observed deformation response, only one quarter of the assembly is considered in a sub-model with refined finite element mesh [Fig. 1(b)]. The global displacement field is imposed on symmetry planes of the quarter sub-model. The diameter, stand-off height and pitch distance of the solder joints is 750 μm, 600 μm and 1.0 mm respectively. All components are assumed perfectly bonded at contact surfaces. The thin layer of copper traces (0.025 mm) is modeled with one layer of linear incompressible modes elements to accurately reproduce the flexing behavior of thin foil. Previous works have observed that fatigue crack path closely follows pad-solder interface [4], [12]. Consequently, an element layer of 50 μm-thick at the solder interface is used to average the plastic strain energy density for use in the life prediction model.

Unified inelastic strain theory defines the visco-plastic response of the 60 Sn–40 Pb (wt. %) solder alloys [17]–[19]. The constitutive stress-strain equations are represented by Anand model as [17]

$$\dot{\varepsilon}_P = A \exp\left(-\frac{Q}{RT}\right) \left[\sinh\left(\frac{\sigma}{\xi}\right)\right]^{1/m}$$

(1)

where $\dot{\varepsilon}_P$ is the inelastic strain rate, $A$ and $m$ are coefficient and strain-rate sensitivity exponent, respectively, $Q$ is the activation energy for creep, $R$ is the gas constant, $T$ is temperature in Kelvin scale, $\xi$ is the stress multiplier and $\sigma$ is the current stress. The deformation resistance, $\bar{s}$ is given by an evolution equation as

$$\bar{s} = \left|h_0 \left|1 - s/s^*\right|^\alpha \right| \cdot \sigma \cdot \left|1 - \frac{s}{s^*}\right| \cdot \dot{\varepsilon}_P,$$

(2)

The parameters $h_0$ is the hardening/softening constant and $\alpha$ represents the corresponding strain rate sensitivity. The saturation value of the resistance, $s^*$ is given by

$$s^* = \bar{s} \left[\frac{\dot{\varepsilon}_P}{A} \exp\left(-\frac{Q}{RT}\right)\right]^{1\eta}$$

(3)

with coefficient, $\bar{s}$ and exponent, $\eta$. The numerical values of all parameters have been optimized for 60 Sn–40 Pb solder [19]. Other materials are assumed to behave elastically throughout the temperature range of interest. In addition, orthotropic behavior of FR-4 substrate is considered. Temperature dependent properties of these materials are extracted from published literature and summarized in Table I, [5], [17]–[21].

Loading parameters for temperature cycling (TC1), accelerated temperature cycling by dwell time period (TD1) and mechanical twisting cycles (MT1) employed in this study are summarized in Table II. The effects of residual stresses and strains due to solder reflow process on subsequent thermal fatigue performance of solder joints are examined for thermal fatigue cases.

### III. RESULTS AND DISCUSSION

The finite element results are presented and discussed in terms of the evolution characteristics of stresses and inelastic strains in the critical solder, the stress-strain hysteresis loops and the predicted fatigue life of the solder using available life models. The critical solder joint that had accumulated the greatest inelastic strain during cyclic twisting deformation is the corner solder. In temperature cycling test, the solder joint located at the symmetry plane parallel with the longer side of the Si-die is the most severely strained solder.

#### A. Stress and Strain Distribution

The von Mises stress distribution in the critical solder is compared for both temperature loading and mechanical twisting, as shown in Fig. 2. The stress scale is in MPa. Both temperature cycling and mechanical twisting display similar distribution of stresses in the solder joint for a given geometry of the assembly. Higher stress gradient is predicted for regions near the edge of the solder joint at solder/intermetallic interfaces. Such high stress is favorable to localized yielding of the solder alloy.

The corresponding inelastic strain distribution for the cyclic twisting case [Fig. 2(b)] is illustrated in Fig. 3. Inelastic strain concentration is confined to a small region near the solder interface while the bulk of the solder remains elastic. It is worth noting that stress and inelastic strain concentration in the critical solder joint is greatest near the component (top) side for temperature cycling case and near the board (bottom) side for cyclic mechanical twisting. This result is consistent with those observed of the fatigue cracking that preferentially propagate in the solder at the board side during bending test and near the component side in thermal cycle tests [2]. In temperature
cycling tests, stress relaxation occurred with accompanying visco-plastic strain in the solder, thus temperature cycles accelerate inelastic strain accumulation. Similar creep related failure mechanism can also be induced in the solder joint by performing isothermal cyclic mechanical twisting test of the assembly at elevated temperature.

The evolution of inelastic strain in the solder joint for the three fatigue loading cases considered is illustrated in Fig. 4. Both thermal fatigue cases (TC1 and TD1) started with an initial residual inelastic strain of 1.37% induced during the solder reflow process. Solder reflow was not modeled for mechanical twisting case. Results show that the rate of inelastic strain accumulation per fatigue cycle in the solder joint for both temperature cycling (TC1) and cyclic mechanical twisting (MT1) tests is similar as depicted by the same slope of the curves. The 10-min dwell time period at both peak temperature levels (TD1) accelerates the accumulated inelastic strain. Stress relaxation that manifests over the hold-time period at peak temperature levels is accompanied by visco-plastic deformation. Cyclic twisting test, if conducted at higher temperature is expected to generate similar creep-fatigue interaction effect.

**B. Stress-Strain Hysteresis**

The stress-strain hysteresis response of the solder alloy for the first five mechanical twist cycles of the assembly is shown in Fig. 5. The shear component (23-direction, parallel to the solder/pad interface plane) displays the largest total strain range of 1.2% with the corresponding shear stress range of 13.0 MPa. This large relative displacement within the solder/intermetallic interface attenuates the cyclic interfacial shear stress and strain resulting in crack initiation, as often observed experimentally [2]. The largest stress range of 50.0 MPa is predicted for the normal component (22-direction, parallel to the axis of the solder joint). The tensile part of this stress is favorable to Mode-I crack initiation at the brittle solder/intermetallic interface layer. The ranking of stress and strain ranges by magnitude is similar for both cases of temperature cycling and cyclic mechanical twisting.

The fifth hysteresis loops of the shear stress-strain component for all load cases are compared in Fig. 6. The hysteresis loops for temperature cycles, TC1 and TD1 are shifted away from the coordinate origin due to the locked-in residual stress and strain induced during solder reflow process. Although the shapes of the shear loops are different for thermal and mechanical fatigue, the stress and plastic strain ranges (for TC1 and MT1) are comparable. This plastic strain range is postulated to govern fatigue life of the solder joint. Larger strain range for load case TD1 suggests shorter expected fatigue life (cycles) of the solder joints compared to TC1.

**C. Solder Fatigue Life Prediction**

Since low cycle fatigue of solder is governed by temperature, strain rate and stress dependence occurrence of dissipative deformation processes, both inelastic strain and dissipative strain energy or plastic work represent suitable indicators...
Fig. 2. Stress distribution in the critical solder: (a) at 25 °C after accumulating four temperature cycles, TC1 and (b) at 0.5° twist during the fifth cycle. (Note the different orientation of each critical solder joint).

Fig. 3. Inelastic strain distribution in the critical solder corresponding to the mechanical stress shown in Fig. 2(b).

Fig. 4. Evolution of inelastic strain in the solder joint for different fatigue load cases considered.

Fig. 5. Hysteresis loops for Cartesian stress-strain components during mechanical twist cycles at 25 °C. Indices 11, 22, and 33 refer to the cartesian coordinate axes.

Fig. 6. Comparison of shear stress-strain hysteresis loops for mechanical twist cycles (MT1), temperature cycles (TC1) and accelerated temperature cycles (TD1).

to evaluate cyclic damage. The calculated plastic shear strain range, $\Delta \gamma_p$, for temperature cycling load cases is used with the Coffin–Manson relation in the fatigue life prediction model. The coefficient and exponent of the strain-based model have been
TABLE III

<table>
<thead>
<tr>
<th>Load Case</th>
<th>( \Delta Y_p ) (psi)</th>
<th>( \Delta W_{ave} )</th>
<th>Predicted life, ( N_f ) (Cycles [Days])</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC1</td>
<td>0.00620</td>
<td>1.566</td>
<td>27556 [191] 34212 [238]</td>
</tr>
<tr>
<td>TD1</td>
<td>0.01026</td>
<td>2.668</td>
<td>10263 [214] 18227 [380]</td>
</tr>
<tr>
<td>MT1</td>
<td>0.00817</td>
<td>2.088</td>
<td>-na-</td>
</tr>
</tbody>
</table>

\[
N_f = 1.2928 \left( \Delta Y_p \right)^{1.96} \tag{4}
\]

where \( N_f \) is the fatigue life (cycles) of the solder. Darveaux forward a fatigue life prediction model for viscoplastic solder based on plastic strain energy density [16], [22], [23]

\[
N_f = N_o + \frac{\alpha}{da/dN} \tag{5}
\]

\[
N_o = 13173 \left( \Delta W_{ave} \right)^{-1.45} \tag{6}
\]

\[
da/dN = 3.92 \times 10^{-7} \left( \Delta W_{ave} \right)^{1.12} \tag{7}
\]

where \( N_o \) is the cycles for the crack initiation, \( \alpha \) is the characteristic crack length (pad diameter), and \( da/dN \) is the crack propagation rate. The term \( \Delta W_{ave} \) is the volume averaging of the plastic work density accumulated per cycle for elements at the interface with thickness of 50 \( \mu \)m. This volume averaging reduces the sensitivity of the calculated strain energy density to mesh size. The calculated strain energy density or plastic work density, \( \Delta W_{ave} \), and the corresponding fatigue lives of the solder for the three load cases are summarized in Table III. Although the absolute fatigue life prediction is desirable, a life prediction accuracy of \( \pm 50 \) \% is generally adequate in view of the complex nature of solder creep behavior and uncertainty in the board level temperature cycling tests [24]. In addition, the different creep models and finite element assumptions only affect the absolute fatigue life, but not the relative trend of fatigue performance [24], [25].

This relative design trend can be evaluated in terms of plastic work density, \( \Delta W_{ave} \), with reasonable range of fatigue lives. Previous work on different TFBGA packages with eutectic solders indicated that \( \Delta W_{ave} \) ranges from 0.154 to 0.175 MPa [24]. In an experimental validation study, 2512-type resistors with 60Sn–40Pb solders were subjected to temperature ranges of \(-55 \) to \( 125 \) \(^\circ\)C (4.5 \(^\circ\)C/min) and \(-40 \) to \( 120 \) \(^\circ\)C (4.0 \(^\circ\)C/min). The calculated \( \Delta W_{ave} \) are 7.3 and 6.0 MPa, respectively [26]. The low magnitude of plastic work density calculated in this study (\( \Delta W_{ave} = 0.0108 \) MPa or 1.566 psi for load case TC1) is attributed to the fast temperature ramp rate of 33 \(^\circ\)C/min. This fast temperature ramp rate lowers the relative accumulation of inelastic strains per cycle, thus contributing to longer characteristic life.

As expected, it is noted that the accelerated temperature cycling by 10-min dwell time period (TD1) results in shorter life (smaller number of fatigue cycles to failure) of solder joint when compare to temperature cycling (TC1). However, the corresponding reliability testing time is longer. In this respect, thermal shock test is perhaps a favorable alternative for accelerated test. Cyclic mechanical twisting (MT1), for similar rate of inelastic strain accumulation, predicts a moderate number of fatigue cycles to failure but at much shorter testing time. Isothermal mechanical test at elevated temperature could further accelerate the fatigue damage process. Correlations between cyclic mechanical twisting data and temperature cycling test data can be made using Weibull statistics to obtain the acceleration or scale factor for the given geometry and design of the assembly. In addition, isothermal test condition and mechanical twisting load magnitude and frequency are easily achieved in an actual reliability test. In this respect, FEA simulations can be effectively utilized to optimize the accelerated cyclic mechanical test profile.

**REFERENCES**


