Introductory invited paper

Solder joint fatigue models: review and applicability to chip scale packages

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Abstract

A review of fourteen solder joint fatigue models is presented here with an emphasis on summarizing the features and applications of each fatigue model. The models are classified into five categories: stress-based, plastic strain-based, creep strain-based, energy-based, and damage-based. Fatigue models falling outside these categories are categorized as 'other empirical models'. Each model is presented under one category with the relevant parameters and applicable packages. Following each category, common issues such as thermal cycling conditions, solder joint geometry, and coverage are addressed. Two fatigue model application scenarios are discussed. In the first scenario, a set of existing fatigue test data is given to the engineer who must determine how best to interpret the data and which fatigue model(s) best apply. In the second scenario, a test scheme must be devised for a new chip scale package product. The number of cycles to failure ($N_f$) or fatigue life must be determined. A general procedure is presented for choosing an appropriate fatigue model(s) based on the package conditions and limited Finite Element Analysis time. This procedure is summarized in a flowchart. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Predicting solder joint fatigue has been one of the electronic industry’s most difficult problems. The newest generation of computer and electronic components features extremely small package sizes with large numbers of connections. Economic factors dictate the small package sizes. The trends in chip packaging have changed from leaded through hole mounted devices to leaded surface mount devices and on to leadless solder ball arrays, which have recently been the focus of concern due to their fine pitch size. At the forefront of this issue is solder joint reliability. Successful prediction of solder joint fatigue failure will depend on the ability to accurately model the solder joint.

Solder joint interconnects serve two important purposes: (1) to form the electrical connection between the component and the substrate, and (2) to form the mechanical bond that holds the component to the substrate. The shrinking interconnect size brings solder joint reliability to the forefront. The most important question is: ‘How long will this component last?’ To answer this question, the failure mechanism must be examined.

Focusing specifically on the mechanical wearout mechanism, most fatigue failures can be attributed to thermomechanical stresses in the soldered joints, caused by differences in the coefficient of thermal expansion (CTE). Most components are mounted on
FR-4 substrates that can expand and contract at rates different from that of the components. This CTE mismatch can strain solder joint connections, and over the component lifetime can contribute to mechanical solder joint fatigue failure. This is especially true for solders. Eutectic 63Sn/37Pb solder, for instance, has been studied extensively and it is well known to be subject to creep. This is predicted not only by the fact that room temperature is greater than one half of the homologous temperature for 63Sn/37Pb solder, but is also evidenced by numerous experimental studies. With the shrinking interconnect size, the solder joint becomes the weakest link and, therefore, must be carefully designed against fatigue.

Early solder joint fatigue models were developed based on experimental thermal cycling tests. Most models that address fatigue require stress–strain data in order to predict service life. Early fatigue data was collected experimentally using strain gauges. However, with the decreasing size of the solder joint, experimental collection of stress–strain data is becoming increasingly difficult, and Finite Element Analysis (FEA) is becoming the more practical route for obtaining stress–strain relationships. Rapid thermal cycling of actual parts is still necessary for verifying the life predictions.

The necessity to model the fatigue behavior of solder joints has also been recognized by other investigators; as a result several solder joint fatigue models have been proposed. However, the assumptions and applicability of these models vary, including the manner in which the physical and metallurgical aspects of fatigue are taken into account. In order to aid appropriate application of the models proposed so far, this critical review was undertaken.

From the published literature, fourteen solder joint fatigue models were identified. These were reviewed to determine the bases upon which they were built, the package types that they are suited for, and the material properties required.

2. General approach to fatigue modeling

Fatigue modeling consists of four primary steps. This process is important as it places a sequence onto what may otherwise be a confusing process. First, a theoretical or constitutive equation, which forms the basis for modeling, is either defined or chosen. Appropriate assumptions need to be made in constructing the constitutive equation. Second, the constitutive equation is translated into a FEA program and a model created. The FEA program calculates the predicted stress–strain values for the system under study and returns stress values for the simulated conditions.

Third, the FEA results are used to create a model predicting the number of cycles to failure, N_{f}. Fourth, the model or results must be tested and verified using thermal cycling data. These four steps describe the general process by which fatigue modeling is developed, implemented, or verified.

The constitutive relation describes the various factors involved and acts as the starting point in solder joint fatigue. The most frequently used constitutive relation is shown in Eq. (1) [1].

\[ \dot{\gamma} = \dot{\gamma}_e + \dot{\gamma}_p + \dot{\gamma}_c \]  

(1)

Here \( \dot{\gamma} \) is the total shear strain, \( \dot{\gamma}_e \) is the elastic shear strain component, \( \dot{\gamma}_p \) is the plastic strain component, and \( \dot{\gamma}_c \) is the creep strain component. The total strain is broken into three components: elastic, plastic, and creep. Separating each of these components in actual life testing can be difficult and often leads to inconsistencies in the final results. Recent research efforts have focused on constructing unified constitutive models and damage evolution for solder joint fatigue life prediction. A complete discussion of constitutive equations is beyond the scope of this paper, and the reader is encouraged to seek other sources for greater detail [1–5].

Once a constitutive equation is chosen, it can be implemented within a FEA code. Assumptions need to be made in order to simplify the equations. For example, one simplification typically made was to neglect the creep strain component and assume contributions from only plastic and elastic strain. This simplified the solution, but assumed negligible creep, which invariably needs to be accounted for when analyzing solder joints. Even with these simplifications, the equations can be complex, requiring numerical integration techniques to solve them. FEA simulation programs such as ABAQUS and ANSYS are some examples of commercially available FEA software programs that are capable of performing the analysis. The FEA models are used to determine the stress–strain relationships, which allows fatigue models to be constructed. In order to increase the accuracy of fatigue modeling, there is constant rethinking of how to theoretically compose newer and more accurate constitutive equations that will lead to more accurate fatigue life predictions.

2.1. Fatigue failure

The manner in which fatigue failure is defined plays a critical role in understanding the fatigue modeling that is done, and consequently the validity of the model employed. In the literature, there are wide discrepancies on how ‘fatigue failure’ is interpreted. In a classical metallurgical sense, ‘fatigue failures’ will occur when the component experiences cyclic stresses and strains that
produce permanent damage' [6]. Inherent to fatigue failures are dynamic and fluctuating/cyclic stresses. Under long term repetitive use, failure can occur at stresses well below the ultimate tensile or yield stresses.

There are two major components to fatigue failures/fractures: the initiation of fatigue cracks and the propagation of these cracks under cyclic loading. The direction of crack propagation is orthogonal to the direction of the principal stress.

In reality, given the configuration of microelectronic packages, it is extremely difficult to monitor and track the initiation and propagation of fatigue cracks. Those who have studied fatigue failures so far, therefore, have to define expedient failure criteria appropriate to the purpose of their research. Some fatigue failure criteria used by other investigators include complete electrical circuit opens, a 50% reduction in the measured stress amplitude on the solder joint, and a 20% crack propagation across the solder joint. When comparing the fatigue life data from various sources, it is important to take into account the definition of the solder joint fatigue failure employed.

2.2. Fatigue models

The models proposed for predicting the fatigue life of solder joints can be divided into five major categories, based on the fundamental mechanism viewed as being responsible for inducing damage. These five categories are (a) stress-based, (b) plastic strain-based, (c) creep strain-based, (d) energy-based, and (e) damage accumulation based, and are tabulated in Table 1, along with the researchers who originally proposed or applied these models. Fatigue models that do not fit into one of the five categories listed above, and are empirically based, have been grouped under a separate category labeled 'other'. The third column in Table 1 denotes the corresponding equation numbers as referred to within this paper.

The stress-based classification is based on the application of a force or stress to a component, causing a resultant strain. Typically, stress-based fatigue applies to vibrational or physically shocked or stressed components [7] and none of the fatigue models reviewed here fall into this category. However, this classification is listed here for completeness. In the strain-based fatigue models a strain is applied, resulting in stresses within a component. Thermal fatigue-induced strains from CTE mismatch fall under this category. The types of strain-induced fatigue can be further divided into two groups, namely plastic strain or creep strain. Plastic strain deformation focuses on the time-independent plastic effects, while creep strain accounts for the time-dependent effects [8]. The very nature of solder lends itself to creep deformation and so must be accounted for. The energy-based fatigue models are the newest models in use today, and are based on calculating the overall stress-strain hysteresis energy of the system or solder joint. Damage-based fatigue models are based on calculating the accumulated damage caused by crack propagation through the solder connection and is developed based on a fracture mechanics approach. These models, along with their assumptions, are reviewed below.

In Table 2, the fourteen solder joint fatigue models are summarized and arranged by class. For instance, fatigue models 1 through 4 (Eqs. (2)-(5)) are the plastic-strain fatigue models, while fatigue models 8

<table>
<thead>
<tr>
<th>Fatigue model</th>
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<th>Strain</th>
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<th>Other</th>
</tr>
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<td>Coffin-Manson</td>
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<td>×</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total strain</td>
<td>3</td>
<td>×</td>
<td></td>
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<td></td>
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<tr>
<td>Soloman</td>
<td>4</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Engelmaier</td>
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<td></td>
<td>×</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Miner</td>
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<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knecht and Fox</td>
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<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syed</td>
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<td></td>
<td>×</td>
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<tr>
<td>Akay</td>
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<td>×</td>
<td></td>
<td></td>
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<tr>
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<td>×</td>
<td></td>
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</tr>
<tr>
<td>Darveaux</td>
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<td></td>
<td></td>
<td>×</td>
<td></td>
</tr>
<tr>
<td>Stolkarts</td>
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<td>×</td>
<td></td>
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<tr>
<td>Norris and Landzberg</td>
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<td></td>
<td></td>
<td>×</td>
<td></td>
<td></td>
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<tr>
<td>Fatigue model</td>
<td>Equation nos.</td>
<td>Model class</td>
<td>Applicable packages</td>
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<td>---------------------------------------------------------------------------</td>
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<td>Coffin-Manson</td>
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<td>$\sigma = \text{fatigue ductility exponent}$</td>
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<tr>
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</tr>
<tr>
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<td>Matrix creep</td>
<td>All</td>
<td>Matrix creep shear strain</td>
<td>Matrix creep only</td>
<td>$E_{acc} = \text{accumulated equivalent matrix creep}$</td>
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<td>Energy</td>
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<td>$W_s = 0.1573, k = -0.6342$</td>
</tr>
<tr>
<td>Liang</td>
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<td>Stress/strain energy density based</td>
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<td>Constants from isothermal low cycle fatigue tests</td>
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<tr>
<td>Heinrich</td>
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<td>$W_s = \text{stress strain hysteresis energy}$</td>
</tr>
<tr>
<td>Darveaux</td>
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<td>$a = \text{total possible crack length}$</td>
</tr>
<tr>
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<td>$\Delta L = \text{crack growth, } N_c = \text{crack initiation}$</td>
</tr>
<tr>
<td>Norris and Landsberg</td>
<td>19</td>
<td>Temperature and frequency</td>
<td>All</td>
<td>Temperature frequency</td>
<td>Test condition versus use conditions</td>
<td>$C = \text{strain energy density}$</td>
</tr>
</tbody>
</table>

$E_{acc} = \text{accumulated equivalent ultimate strain}$

$k = \text{material constant}$

$\Phi, \Phi' = \text{isothermal fatigue life ratio}$

$T = \text{temperature}$
through 12 (Eqs. (10)–(14) and (17)) reflect the energy-based fatigue models. 'Applicable packages' refers to IC packages that the fatigue models have been tested for. 'Required parameters' refers to the actual variables within the models, such as strain range, energy curves, and damage accumulation; knowledge of which is required for the models to be run. 'Coverage' refers to the service conditions and solder joint loading mechanisms for which the model is relevant. Coffin-Manson, for example, is considered a low cycle fatigue model. 'Constants' refers to the constants required for application of the fatigue model (such as the fatigue strength exponent).

2.2.1. Plastic strain fatigue models

As listed in Table 1 Coffin-Manson, Solomon, Engelman, and Miner have proposed solder joint fatigue models based on plastic strain. Each of these models predicts failure — or cycles to failure — based on calculation or experimental determination of the applied plastic shear strain. The Coffin-Manson fatigue model is perhaps the best known and most widely used approach today. The total number of cycles to failure, \( N_f \), is depicted as being dependent on the plastic strain amplitude, \( \Delta \varepsilon_p \), the fatigue ductility coefficient, \( \varepsilon_f' \), and the fatigue ductility exponent, \( c \). The relationship among these variables is shown in Eq. (2) [9].

\[
\frac{\Delta \varepsilon_p}{2} = \varepsilon_f'(2N_f)^c
\]  

(2)

The fatigue ductility coefficient, \( \varepsilon_f' \), is approximately equal to the true fracture ductility, \( \varepsilon_f \). The fatigue ductility exponent, \( c \), varies between \(-0.5\) and \(-0.7\) [10]. Originally proposed to predict the fatigue life of metals in the aircraft industry, a variety of strain life engineering data is available on steels and other metals [11]. Experimental data are required to determine the constants, and are typically collected by application of strain gauges. Actual fatigue tests, however, are often time consuming and the results are usually applicable only to the specific geometry of the solder joint. For small solder joints, FEA modeling can be used to determine the plastic strains which are then used to predict the fatigue life. This version of the Coffin-Manson relation assumes that fatigue failure is strictly due to plastic deformation and that elastic strains contribute only a small portion to fatigue failure.

Because the Coffin-Manson equation considers only plastic deformations, it is commonly combined with Basquin’s equation to account for elastic deformation as well. The resulting equation is known as the Total Strain equation, and is shown in Eq. (3) [9].

\[
\frac{\Delta \varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f(2N_f)^c
\]  

(3)

\(\Delta \varepsilon\) is the strain range, \(\sigma_f'\) is the fatigue strength coefficient, \(E\) is the elastic modulus, \(\varepsilon_f\) is the fatigue ductility, \(b\) is the fatigue strength exponent (Basquin’s exponent), and \(c\) is the fatigue ductility exponent. This fatigue model is an improvement over the Coffin-Manson equation in that it also accounts for the elastic contribution to fatigue failure. As can be seen in Fig. 1, the low cycle region to the left of \(N_f\) is governed by

![Fig. 1. Total strain versus life equation.](image-url)
the plastic-strain amplitude (Coffin-Manson equation), and the high cycle region to the right of \( N_I \) is
governed by the elastic-strain amplitude (Basquin’s equation) [12].

Solomon’s [13] low cycle fatigue model relating the plastic shear strain to fatigue life cycles is shown in
Eq. (4),

\[
\Delta \gamma_p N_p^2 = \theta
\]  

(4)

\( \Delta \gamma_p \) is the plastic shear strain range, \( N_p \) is the number of cycles to failure, \( \theta \) is the inverse of the fatigue ductility coefficient, and \( \alpha \) is a material constant. This fatigue model relates fatigue behavior to the plastic shear strain imposed on the specimen, and requires data collection or determination of the experimental plastic strain range. This fatigue model has been applied to leaded plastic quad flat packages and underfilled Flip Chip by various authors with success. However, since this model does not account for creep, it is limited in its practical use for solder joints [13–15].

The Engelman’s fatigue model is shown in Eq. (5). The total number of cycles to failure is related to the total shear strain, \( \Delta \gamma_I \), the fatigue ductility coefficient, \( \gamma_p \), and the variable, \( c \), which is a function of frequency and temperature [13].

\[
\frac{1}{N_I} = \frac{1}{2} \left( \frac{\gamma_p}{2 \tilde{T}_I} \right)^{1/c}
\]  

(5)

where \( c = -0.442 - 6 \times 10^{-4} \tilde{T}_I + 1.74 \times 10^{-5} \text{ln}(1 + f) \), \( \tilde{T}_I \) is the mean cyclic solder joint temperature in °C, and \( f \) is the cyclic frequency in cycles/day. Pang et al. [13] reported a \( 2 \gamma_p \approx 0.65 \) in applying Engelman’s fatigue model to underfilled Flip Chip. This fatigue model improves on Solomon’s and Coffin-Manson by including cyclic frequency effects, temperature effects, and elastic–plastic strains. It is, however, based on isothermal experimental fatigue data, implying prior testing knowledge of the solder joint of interest.

By applying Miner’s linear superposition principal, both plastic and creep strain can be accounted for in a strain-based fatigue model. This model combines the Solomon fatigue model with the Knecht and Fox creep model, and is shown in Eq. (6) [13–15].

\[
\frac{1}{N_c} = \frac{1}{N_p} + \frac{1}{N_c}
\]  

(6)

\( N_p \) refers to the number of cycles to failure due to plastic fatigue and is obtained directly from Solomon’s fatigue model. \( N_c \) refers to the number of cycles to failure due to creep fatigue and is obtained from Knecht and Fox’s creep fatigue model (see Eq. (8)). This fatigue model is similar to a full method reported by Lau et al. as Strain Range Partitioning (SRP). In SRP, a typical hysteresis loop can be separated into four components: the plastic strain in tension and compression (PP), the creep strain in tension and compression (CC), the creep strain (tension-plastic strain in compression (CP) and the plastic strain in tension-creep strain incompressibility (PC). Eq. (7) shows the SRP equation [9].

\[
\frac{1}{N_I} = \frac{F_{pp}}{N_{pp}} + \frac{F_{cc}}{N_{cc}} + \frac{F_{cp}}{N_{cp}} + \frac{F_{pc}}{N_{pc}}
\]  

(7)

\( F_{ij} \) is the fraction of the total inelastic strain range of the hysteresis loop. The contributions to each part are determined from other fatigue models and from cyclic stress–strain tests.

Each of the fatigue models described above considers plastic deformation as the main driving force for fatigue failure; however, a number of factors must be considered before applying these models. Calculation of the number of cycles to failure, \( N_I \), requires knowledge of the plastic strain range, specific to each geometry, from either FEA or experimentation. The experimental conditions surrounding the data collection, such as temperature cycling, ramp rates, dwell times, and variations in strain amplitude must also be taken into account. While some of the plastic strain fatigue models do address some of these factors, application to different solder joint geometries would require new baseline life data.

All of the plastic strain-based fatigue models require some form of geometry specific data to calculate the fatigue life. This information comes from FEA or from experimental work. The Coffin-Manson fatigue model depicted by Eq. (2), for example, requires knowledge of the plastic strain range. This will depend on the solder joint geometry, regardless of whether FEA or experimental methods are used. Schubert et al. [16] and Getkin et al. [17] have used the Coffin-Manson fatigue model and applied it to underfilled Flip Chip. In each case, geometry specific FEA was used to determine the strain range involved. In separate work on BGA style packages, Hong et al. [18], Iwasaki et al. [19], and Rassiaan et al. [20] used various forms of the Coffin-Manson fatigue model and geometry specific FEA to analyze package reliability. The Engelman fatigue model, as shown in Eq. (5), is based on geometry dependent isothermal experimental fatigue data and is also dependent on the value of the constants contained within the equation. In the Solomon fatigue model, the constants \( \alpha \) and \( \theta \) will also depend on solder joint geometry. Subsequently, any change in the solder joint geometry will affect the constants used and the number of cycles to failure, \( N_I \).

Thermal cycling conditions must be considered before using these fatigue models. If rapid thermal cycling is performed over a temperature range, the range and type of strains must be determined. Is it jus-
tifiable to assume that the strain is entirely plastic, or should the strain be considered as being elastic–plastic? Another important factor is the extent to which creep is considered. When creep is assumed to be insignificant, the various types of plastic strain range amplitudes must be accounted for. During laboratory fatigue testing thermal cycling conditions are controlled and typically an idealized temperature profile is used as shown in Fig. 2(a). Parts in the field, however, may experience drastically different thermally induced strains owing to various field conditions that are essentially non-ideal as shown in Fig. 2(b) and (c). By comparing the three profiles it can be seen that while \( \Delta \varepsilon_p \) itself may have the same magnitude, the manner in which this is distributed between tensile and compressive components can vary for each condition.

2.2.2. Creep strain fatigue models

Creep strain fatigue models account strictly for the creep phenomenon involved in solder joints. Early attempts at modeling creep were made by isolating the elastic and plastic deformation mechanisms. Although creep phenomena have been studied exhaustively, the fatigue models reviewed here do not fully capture the fatigue process because of the overlap of creep-plastic-elastic deformations. Detailed studies have been performed on microstructure, dislocation movement, and grain boundary effects, but are still not fully integrated into creep models. For solder joints, it is commonly accepted that creep may be due to grain boundary sliding and/or matrix creep (dislocation movement). Within this category, the Knecht and Fox and Syed fatigue models are reviewed.

Creep, as mentioned previously, can be separated into two possible mechanisms, matrix creep and grain boundary creep. Knecht and Fox have proposed a simple matrix creep fatigue model relating the solder microstructure and the matrix creep shear strain range as shown in Eq. (8) [1].

\[
N_f = \frac{C}{\Delta \varepsilon_{mc}} \quad (8)
\]

The number of cycles to failure, \( N_f \), is related to a constant \( C \), which is dependent on failure criteria and solder microstructure. \( \Delta \varepsilon_{mc} \) is the strain range due to matrix creep. Pang et al. [13] have reported fatigue life values for underfilled Flip Chip using this fatigue model.

The second creep mechanism, grain boundary sliding, is incorporated with matrix creep into a fatigue model presented by Syed [21–23]. In this model, creep strain is partitioned into two parts as shown in Eq. (9) [22].

\[
N_f = (0.022D_{gb} + 0.063D_{mc})^{-1} \quad (9)
\]

Here, \( D_{gb} \) and \( D_{mc} \) are the accumulated equivalent creep strain per cycle for grain boundary sliding and the matrix creep, respectively. Results published by Syed on thin small outline packages (TSOP) parts indicated that the dominant mechanism changes from grain boundary sliding to matrix creep for faster ramp rates, stiffer assemblies, and lower temperatures controlling the lower temperature ranges.

Inclusion of creep strain into the fatigue models provides a more comprehensive approach, though appropriateness is still relevant in their application. Thermal cycling dictates the damage mechanisms and conditions, which can include dwell time and strain amplitude. Other factors to consider include the solder microstructure and solder joint geometry.

Rapid thermal cycling typically involves fast cycling, which determines the creep mechanism that will occur. Syed [23] has reported on the factors affecting matrix creep and grain boundary sliding and concluded that a complex number of parameters including dwell times, ramp rate, hold times, high temperature extremes, and low temperature extremes affects the life prediction results. One limitation in the Syed fatigue model is the absence of plastic-strain effects, which is described by Syed as being not applicable to solder alloys at high homologous temperatures and slow rates of temperature change. Plastic strain effects can be neglected only if the strain rate is low enough to be neglected, thus resulting in a constant stress-situation and the strain is indeed time-dependent.

Solder microstructure also plays a key role in creep strain fatigue because it affects the strength of the solder joint and, hence, the fatigue life. Morris and Reynolds [24] have reported on the effect of microstructure on eutectic solder mechanics. Their con-

![Fig. 2. Variable strain ranges.](image)
clusions draw attention to the importance of microstructure in fatigue modeling. They emphasize three important points to watch for: (1) the use of engineering data which is not representative of the actual solder joint of interest, (2) analytical models predicting solder joint behavior without incorporating microstructural effects, and (3) the effect of small impurities on microstructure. The first point refers to solder joint geometry. Data collected from one geometry can lead to erroneous predictions when applied to a different geometry. The engineering material properties of bulk solder are not fully representative of a small solder joint geometry. The second point refers to the importance of solder microstructure, including grain size and shape. Solder joints can have radically varying microstructures, depending on the conditions under which they were formed. The third point refers to small impurities, deliberate or not, which can affect the size or shape of each individual grain, and also strength characteristics.

2.2.3. Energy-based models

Energy-based fatigue models form the largest group of models. These models are used to predict fatigue failure based on a hysteresis energy term or type of volume-weighted average stress–strain history. Fatigue energy is typically calculated using some correlation to the energy under the stress–strain hysteresis loop. Dasgupta [25] has proposed that the total strain energy includes both stress and strain information and that it is a good indicator of solder joint damage. Akay [26] has proposed the following fatigue model, shown in Eq. (10), based on the total strain energy.

\[
N_f = \left( \frac{\Delta W_{\text{total}}}{W_0} \right)^{1/k} 
\]  
(10)

\(N_f\) is the mean cycles to failure, \(\Delta W_{\text{total}}\) is the total strain energy, \(W_0\) and \(k\) are fatigue coefficients. Studies using this model on LLCC leaded package fatigue behavior were reported by Akay. No packages with solder ball joints were investigated. Based on their findings the values of the coefficients were determined to be \(k = -0.6342\) and \(W_0 = 0.1573\) for the leaded joints tested.

Liang et al. [27] have reported a fatigue life prediction methodology that accounts for the geometry of the solder joint based on elastic and creep analyses. The fatigue life is calculated on an energy-based fatigue failure criterion and is shown in Eq. (11).

\[
\tilde{N}_f = C(W_{ek})^{-m} 
\]  
(11)

\(W_{ek}\) is the stress–strain hysteresis energy density. \(C\) and \(m\) are temperature-dependent material constants derived from low cycle fatigue tests. The author reports that this fatigue life model is similar to other energy-based fatigue models proposed by Engelmaier in 1991, Morrow in 1964 and Liang and Pelloux in 1989. Liang reports testing of BGA packages for verification of this model.

Wu et al. [28] studied the reliability of fine pitch BGA packages using Heinrich’s energy fatigue model, as shown in Eq. (12).

\[
N_0 = 18083\Delta W^{-1.46} 
\]  
(12)

\(N_0\) is the number of cycles to crack initiation and \(\Delta W\) is the viscoplastic strain energy density per cycle (psi). Jung et al. [29] performed fatigue analysis for crack initiation in PBGA packages, using a similar approach, as depicted in Eq. (13). The results for 62Sn/36Pb/2Ag solder joints was reported.

\[
N_0 = 7860\Delta W^{-1.00} 
\]  
(13)

\(\Delta W\) (psi) is the viscoplastic strain energy density and is defined as ‘the summation of the product between stress and inelastic strain increment vectors over the number of converged subsets’ [30]. Eqs. (12) and (13) are based on life prediction models as derived by Darveaux. It is important to remember that these models calculate the number of cycles to crack initiation, namely, the total energy that must accumulate in the solder joint in order to initiate cracks. Total failure is not addressed. Linking the crack initiation with the actual cycles to failure requires the inclusion of crack propagation.

Gustafsson [31] has reported another energy based fatigue model, based on findings from Darveaux, as depicted in Eq. (14).

\[
N_{av} = N_0 + \frac{a - (N_{av} - N_{av}) \frac{da}{dN}}{\frac{da}{dN} + \frac{dN}{dN}} 
\]  
(14)

In this equation, the overall time to failure is obtained from a combination of crack initiation and crack propagation. For each of these mechanisms, i.e., initiation and propagation, it is viewed that there are primary and secondary cracks, indicated by the subscripts ‘p’ and ‘s’, respectively. The primary and secondary cracks are thought to initiate and propagate towards each other at different rates. \(N_{av}\) is the number of cycles to failure and \(a\) is the total possible crack length. \(N_{av}\) and \(N_0\) are the primary and secondary crack initiation energy based terms, respectively, and are calculated using Eq. (15) [31], by first determining the appropriate value of \(\Delta W\) from the hysteresis curves for each.

\[
N_{av}, N_0 = 54.2\Delta W^{-1.00} 
\]  
(15)
Early attempts that only used the energy-based fatigue models lacked accuracy due to their inability to incorporate solder joint crack propagation. Crack propagation models were created and coupled with the crack initiation models. The Darveaux fatigue model shown in Eq. (14) is an example of an energy-based fatigue model that incorporates crack propagation. The crack propagation terms, $da/dN$, are dependent on the corresponding values of $\Delta W$, as shown in Eq. (16) [31].

$$\frac{da}{dN} = 3.49 \times 10^{-7} \Delta W^{1.13}$$  \hspace{1cm} (16)

In general, $\Delta W$ is the energy density term calculated from the stress–strain hysteresis curve. FEA simulation results reported by Gustafsson were based on leadless RF-transistor solder joints.

Pan reports a strain-energy based fatigue model called ‘critical accumulated strain energy’ or CASE. This model is based on the assumption that the strain energy accumulates during thermal cycling and eventually reaches a critical value, \( C \). This fatigue model is shown in Eq. (17) [32].

$$C = N_f^s \left( aE_y + bE_c \right)$$  \hspace{1cm} (17)

\( N_f^s \) is the number of cycles to failure. \( C \) is defined as the critical strain energy density and was reported to be 4.55 Mpa/mm\(^3\) for the range of tests performed. The constants \( a \) and \( b \) are essentially determined from multiple linear regression of FEA results. The creep and plastic energies denoted by \( E_y \) and \( E_c \) were also calculated by FEA. For this model, Pan used the experimental data reported by Hall and Sherry (1986), which was collected for a leadless ceramic chip carrier (LCCC) package on printed wiring board assemblies. A hyperbolic sine steady-state creep law was used to describe creep. This fatigue model assumes that FEA accurately describes both the plastic and creep energies as distinct separable parts.

Energy-based models were the first attempt at adding hysteresis information to fatigue modeling. As with the strain based (plastic and creep) fatigue models, the test conditions applied to the energy-based fatigue models will dictate the fatigue life calculation, with one exception. The energy based fatigue models predict the accumulated energy required to initiate a crack; it does not predict when fatigue failure will occur — only that a crack will form. The benefit of an energy-based fatigue model, as compared to the strain-based or creep-based fatigue models, is the ability to capture test conditions with more accuracy. For complex waveform stress–strain hysteresis curves, the energy-based fatigue models are better able to capture the accumulated damage [33].

One limitation of the energy-based fatigue models is their inability to predict the actual number of cycles to failure. Only crack initiation is predicted. It was this shortcoming that led to the addition of crack propagation to fatigue modeling. Crack propagation was not new to solder joint fatigue modeling, but an extension of fracture mechanics into solder joint reliability. In a separate study published by Solomon et al. [34,35], it is pointed out that the energy, \( W \), can be used to correlate fatigue life, but that it is still dependent on temperature and strain rate or cycle frequency. So the application of energy-based fatigue models with crack propagation is being debated.

As is the case with strain based fatigue models, geometry still plays a role in the energy based fatigue models [36]. The size and shape of the soldered joint will dictate the FEA analysis or experimental stress–strain measurements. The resulting hysteresis curve directly affects the calculation of the work energy term, $\Delta W$.

### 2.3. Damage fatigue models

This particular classification for fatigue models involves calculating the overall damage done to the solder joint. Stolkarts [37] has reported successful application of this model over a damage-free model. Eq. (18) depicts the equation used by Stolkarts in calculating the number of cycles to failure, \( N_f \).

$$N_f = \frac{1 - (1 - d_f)^{k^{-1}}}{(k + 1)L}$$  \hspace{1cm} (18)

\( d_f \) is the amount of damage at failure and is taken as 0.5 for solders, \( k \) is defined as a material constant and given a value of 2. \( L \) is defined as \( L = \int f \frac{dt}{\Delta t} \approx \text{constant} \), where is ‘an initial rate of damage of remaining undamaged material in the representative volume element’.) The essential parts of this equation encompass unified creep-plasticity models with an internal damage parameter. Modeling on 60Sn/36Pb/2Ag and 60Sn/40Pb solder was reported.

Damage-based fatigue models have their basis in either fracture mechanisms or creep and fatigue mechanisms. The Stolkarts fatigue model has its basis in a constitutive derivation involving creep-plasticity. The introduction of a damage parameter, \( d \), allows calculation of the number of cycles to failure. The stress–strain hysteresis loop is still used in the calculation to determine the amount of damage. This fatigue model is capable of incorporating loading with and without hold times and can handle various thermal cycling dwell times and ramp rates.

As with the strain-based and energy-based fatigue models, solder joint geometry still plays a key role. Application of the damage-based fatigue model
requires FEA to effectively obtain a solution and any FEA analysis is geometry specific.

As with the other fatigue models, microstructure is not directly addressed by the damage-based fatigue model. The approach is more focused on the constitutive theoretical level and is strongly dependent on FEA for calculation. Therefore, application of this type of fatigue model will depend on the amount of FEA modeling the user is willing to expend.

2.4. Other empirical models

These last fatigue models reviewed were reported on by Mei [38] on the solder joint reliability of TSOP and Lau and Pao [39]. In lieu of actual fatigue life calculations, acceleration factors are computed using various forms of the Coffin-Manson equations. The acceleration factors (AF) are shown in Eqs. (19)–(21) and defined as the ratio of the life at the use condition (u-subscript) to the life at the accelerated test condition (t-subscript).

\[
AF = \left( \frac{\Delta T_u}{\Delta T_t} \right)^{2} \left( \frac{T_u}{T_t} \right)^{1/3} \left( \frac{\phi_u}{\phi_t} \right)
\]  

(19)

\[
AF = \left( \frac{\Delta T_u}{\Delta T_t} \right)^{2} \left( \frac{T_u}{T_t} \right)^{1/3} e^{4(1/\Delta T_u-1/\Delta T_t)}
\]  

(20)

\[
AF = \left( \frac{T_u}{T_t} \right)^{2} \left( \frac{T_u}{T_t} \right)^{1/3} e^{4(1/\Delta T_u-1/\Delta T_t)}
\]  

(21)

\( \phi_u/\phi_t \) is the isothermal fatigue life ratio at the maximum temperature [38]. Eqs. (20) and (21) are alternative forms of Coffin-Manson where temperature, frequency, and shear strain are used in computing the fatigue life. The subscripts in Eqs. (20) and (21) represent ë-operated and t-accelerated test conditions. Mei reports comparisons of this fatigue model to Engelman's leadless and leaded fatigue life models for TSOP test cases. A comparison was also made using AT&T's Comprehensive Surface Mount Reliability model. Among the conclusions reported for the Norris and Landzberg fatigue model, was a conservative estimated fatigue life result as compared with experimental testing.

Once the AF is determined, the life distribution, reliability function, and failure rate can be calculated from Weibull statistics as shown in Eqs. (22)–(24).

\[
F_0(x_0) = 1 - e^{-((x_0/AF)^\beta)}
\]  

(22)

\[
R_0(x_0) = e^{-((x_0/AF)^\beta)}
\]  

(23)

\[
h_0(x_0) = AF^{-\beta}(\beta/0)(x_0/0)^{\beta-1}
\]  

(24)

The interested reader is referred to Lau [39] who demonstrates this technique.

To make practical use of these modified Coffin-Manson equations, one needs only the test and operating conditions — one important point made by Mei in relating accelerated tests to fatigue life conditions. In accelerated thermal cycling tests, extreme temperature changes create failures. These changes may cause failure plastically rather than through creep mechanisms.

3. Practical engineering application guidelines for application of fatigue modeling to a CSP style ball interconnect

Up to this point, the discussion has mainly focused on the available fatigue models within the literature, the relevant equations, the applications, and the limitations. Consider two possible fatigue prediction scenarios on how such models can be applied to Chip Scale Packaging (CSP). In the first scenario, experimental fatigue failure data has been collected on a wafer level CSP. Nguyen, et al. [40] have reported such failure data for this thermal cycle tests on CSPs. The packages were tested at specific intervals and the number of solder joint failures (i.e., electrical opens) was recorded. The failure data was reported as the total number of parts failed as a function of the number of cycles. Given this scenario, the requirement is to determine the quickest and most effective means for evaluating the fatigue data and predicting fatigue life. This scenario is often considered as an engineer’s worst nightmare. New packages are frequently created and rushed to market with little or no time devoted to determining fatigue life characteristics. Customers often require such information, which can differ from customer to customer. For instance, customer ‘A’ may require thermal cycling information based on a –40–125°C with a 5 min ramp rate, 20 min dwell, and 1 cycle/h, while customer ‘B’ may require a –20 to 150°C with a 10 min ramp rate and 2 cycles/h. For the production engineer, a quick means of determining the fatigue life would be timesaver.

As a first approach, the AF can be computed for an initial fatigue life. This calculation is simple, requiring only the temperature ranges and frequency conditions. Eq. (20), for example, utilizes the frequency, temperature and operating/testing conditions to calculate the AF. From an AF, a Weibull statistics failure distribution can be obtained by employing Eqs. (20)–(24). The benefits of this technique are: (1) no FEA calculations or modeling, (2) no complex curve fitting or strain hysteresis curve estimations, and (3) rapid fatigue life predictions.
The drawbacks of this technique are: (1) microstructural effects are unaccounted for, (2) damage mechanisms are unaccounted for, and (3) solder joint geometry is neglected.

As a second approach, FEA must be performed. This involves choosing a viable constitutive equation and creating the fatigue model (2D or 3D). A 2D model will yield quicker results over a 3D model and consumes less computation time. The modeling must be done to obtain the stress-strain relationships and the hysteresis curve. With the FEA solutions, the strain range can be determined for application of any of the plastic strain-based fatigue models. The Engelmaier fatigue model shown in Eq. (5) has the added benefit of not requiring separation of elastic and plastic strains. Application of the Coffin-Manson, Miner, Solomon, or Total Strain equations, requires the FEA to include calculation and separation of the plastic-strain components from the elastic and creep-based components. This

Fig. 3. General procedure for choosing an applicable fatigue model.
step requires additional programming resources and relies on the constitutive models to provide accurate representation of the phenomena.

With additional resources and time, a more accurate fatigue life calculation might be obtained using one of the energy-based fatigue models. While the previous FEA calculations provide the necessary hysteresis curve, as Solomon [34] points out, the plastic strain and not the hysteresis curve appears to be the true governing factor in determining the fatigue life. In other words, according to Solomon, it is the plastic strain, and not energy, that is the primary determining factor.

A fracture mechanics-based fatigue life estimation is at best complicated and somewhat unproven at this point in time. To obtain practical fatigue life estimations, a fracture initiation point is required. With the small solder joint geometry in CSP packaging, the fatigue life estimation is at best only an estimation which has not been proven as more accurate than the strain or creep-based fatigue models.

In the second scenario, a new CSP product is to be introduced and some determination must be made of the product’s fatigue life. To pick a proper fatigue model, the operating conditions of the device must be determined. The type of fatigue model applied can be based on the following five parameters: operating temperature, cycling frequency, dwell time, ramp rate, and strain amplitude. These five parameters are not exclusive and other parameters may need to be included. Using these operating conditions, low cycle fatigue tests can be performed to gather essential baseline data needed to calculate fatigue model constants. Some values for these constants may be available in the literature, but for new products, such as CSPs, the values may not be applicable. Choosing an applicable fatigue model will ultimately come down to one major consideration: the time available to do the fatigue modeling.

Time will always be the deciding factor. Given an infinite amount of time, all of the fatigue models can be applied and the fatigue life predictions reported, however impractical this seems. To this end, a general procedure flowchart is shown in Fig. 3 outlining the approach that can be applied to assist the user in choosing a fatigue model. Each key step is based on saving time. Given enough time, a more in depth analysis can be performed. As shown in Fig. 3, the first key step is the decision to perform any FEA analysis. If no analysis is performed, then AF are the most logical choice of fatigue modeling. If FEA is planned, then by utilizing knowledge of the products’ operating conditions, an estimation and determination can be made as to whether creep strain fatigue or plastic strain fatigue will dominate. It is at this point that experimental data must be collected. This information can come from low cycle fatigue tests or other sources such as available literature data. This data must be collected for use in determining the values of constants for some of the fatigue models. In conjunction with the experimental data collection, a simple stress–strain analysis can be performed using FEA. Using this information, a fatigue model choice can be made using a plastic strain-based or creep strain-based fatigue model (Coffin-Manson, Knecht and Fox, etc). Time permitting, a more detailed FEA can be performed to predict the hysteresis curve and an energy-based fatigue model (e.g., Dasgupta’s Eq. (10) can be used. At this engineering stage, applying a fracture mechanics-based approach such as Darveaux’s fatigue model can reveal more in-depth information as to crack initiation and propagation.

4. Summary

The fourteen solder joint fatigue models reviewed can be categorized into one of the five classes: stress-based, plastic strain-based, creep strain-based, energy-based (stress–strain hysteresis), and damage-based (crack propagation). Tables 1 and 2 contain a summary of the fatigue models.

All of the fatigue models reviewed require some form of information related to the specific geometry. Most of the fatigue models have been utilized for life-time predictions of various leadless or leaded packages; some others were applied to BGA or Flip Chip solder joint interconnects. In order to apply the fatigue models, baseline low cycle fatigue testing is usually required to establish the values of the fatigue model constants. This baseline data is of course geometry specific to the solder joint of interest.

Along with solder joint geometry, the thermal cycling conditions affect the fatigue life and must, therefore, be carefully considered. Wrapped within the thermal cycling conditions are the effects of dwell time, ramp rate, temperature range, strain amplitude, and cycling frequency. Early fatigue models failed to capture any aspects of these conditions, and the best models available still consider these parameters empirically. The acceleration factors capture these empirical parameters using a modified Coffin-Manson equation but are limited because mechanistic effects such as crack initiation are ignored.

Another limitation in fatigue modeling is microstructure. All of the fatigue models reviewed do not adequately capture microstructural effects. Syed’s fatigue model encompassing grain boundary sliding and matrix creep does the best job at accounting for these effects, but plastic strain deformations are assumed to be wrapped into these effects. For high operating temperatures, these effects may be the only ones that need
consideration, but that will depend on the individual operating conditions of the part.

Defining fatigue failure appears to be a problem spot as well. Currently, no standard definition, as applied to fatigue modeling, exists for fatigue failure. A few fatigue model studies reported fatigue failure based on electrical conductivity tests (change in resistivity or load drop), while others base calculations on crack initiation. Strict definitions of fatigue failure are required before comparing test results; otherwise incorrect conclusions could be drawn from the data. The most comprehensive fatigue models are the hybrid energy based models. These models incorporate the stress–strain energy history (hysteresis energy). Early versions of these energy fatigue models were inadequate in predicting fatigue failure. Specifically, the hysteresis energy can be a function of temperature, strain rate or cycle frequency. To adequately predict fatigue failure with energy based models, crack propagation equations, based on the same energy terms, are combined into many solder joint fatigue models.

One final important issue surrounding these fatigue models is their constitutive base. If a proper fatigue model must be chosen for modeling, then a proper constitutive base is required to compute stress–strain relationships. Many new constitutive equations are available within the literature and require careful examination before application to a specific solder joint.

References


