On the Life Prediction and Accelerated Testing of Solder Joints

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Abstract

A critical review of the methodologies of life prediction, accelerated testing, and constitutive modeling for solder joint reliability assessment is presented in this paper. Energy-based approach could mislead the life prediction of solder joints under some accelerated conditions. Strain-based approach is strongly recommended to combine with unified constitutive modeling for the reliability assessment of solder joints. The separated constitutive modeling of rate-independent plasticity and creep currently used in literature should be used cautiously, in particular, considering the inconsistency and difficulty for the calibration of model parameters and the Finite Element analysis of solder joints subjected to thermal cyclic loading. The bound concept of fatigue life prediction and the upper bound of the time-to-failure found in this paper for accelerated testing of solder joints are very meaningful for industry practice. In particular, an upper bound of accelerated testing factors was found to reduce the time-to-failure of Flip Chip packages from three years to one week for rapid reliability assessment. Moreover, over accelerated testing temperature is not necessary for underfilled Flip Chip packages, which can result in unrealistic requirement for underfill material selection. The solder joint reliability assessment of the Ford joint specimen, PQFP, and Flip Chip packages by Finite Element analyses enlightens key points addressed in this paper.

Key words:

Reliability, Fatigue Life Prediction, Accelerated Testing, Solder Joints, PQFP Package, and Flip Chip Packages.

1. Introduction

The solder joints play a key role as mechanical and electrical interconnects in advanced packaging technologies such as Ball Grid Array (BGA), Flip Chip package, Chip Scale Package (CSP), Plastic Quad Flat Pack (PQFP), Direct Chip Attach (DCA), and fine pitch SMT assemblies[1,2]. The fatigue failure of solder joints and their life prediction are one of the most important issues of solder joint reliability, in particular, for military, aerospace, and automotive electronics. Design-for-reliability is driven by high-density interconnection, high performance of electronic products, and packaging miniaturization[1-3]. For instance, the 1997 National Technology Roadmap for Semiconductors (NTRS)[3] has predicted the new generations of Flip Chip packages with the targeted need for 50-microns ball pitch in 2012, from the 250-microns ball pitch of current package level. With the shrinking interconnect size, the solder joint can become the weakest link, and therefore, it must be carefully designed against fatigue.

Electronic industries typically subject new product design to a series of reliability qualification tests to prove that the product they are planning to introduce will be sufficiently robust to function in various environments. Product design currently determines 75 percent of manufacturing costs. Additionally, companies pay dearly for product and pre-production prototype failures. Therefore, increasing numbers of manufactures now turn to solidsbased computer-aided design to address escalating electronic packaging challenges[4]. In terms of fatigue failure of solder joints, current paradigm for assessing the in-service reliability of electronic packages is based on thermal/mechanical cycling and thermal shock tests with the humidity, which is a time-consuming practice. Therefore, the accelerated testing becomes more important and the focus of intensive research area recently, driven by short-time-to-market and low-cost. Rapid reliability assessment is then highly desirable for electronic manufacturing industries. Concurrent engineering approaches, in particular, for solder joint reliability assessment, include the methodologies of the life prediction, computer modeling, and accelerated testing of solder joints under various accelerated hygro-thermal-mechanical testing conditions. The evaluation of these methodologies is the objective of this paper.

Solder joints are subjected to very high homologous temperature operation, in particular, under accelerated test conditions. For instance, for eutectic tin/lead solder with the melting point of 183°C, the homologous temperature range is from 0.48 up to 0.87 for thermal cyclic loading ranges of –55°C to 100°C for consumer electronics and –55°C to 125°C for military electronics, respectively. However, for aerospace and automotive electronics, the temperature range of –55°C to 180°C is required for reliability assessment, therefore, high temperature lead-free solders have been developed to find alternatives to eutectic tin/lead solder[5]. It has long been known that solder fatigue life under the high homologous temperature cycling is difficult to predict due to the time/rate/temperature-dependent viscoplastic behaviors of solder alloys. The complicated geometry of solder joints makes the task more difficult. Moreover, the thermal fatigue life of solder joints under accelerated test conditions depends on extreme temperatures (maximum and minimum temperatures), temperature ramping rates, dwell time and dwell temperature, evolution of solder microstructures, presence of intermetallics, soldering defects, and residual strains due to processing. Therefore, the life prediction approaches currently used in the literature only achieve limited successes due to the complicated thermal cyclic loading.

Significant progress has been made in this area recently[1,2,5], including the brief review of solder joint reliability models for Chip Scale packaging[6], solder reliability methodology for the Powermite package[7], critical issues in computational modeling, accelerated testing of the joint reliability for Flip Chip and PBGA packages[8-13], and direct experimental measurement of spatial distributions of thermal residual stress in silicon dice in response to different solder alloys[14].

This paper presents a critical review of life prediction methodology of solder joints which are subjected to thermal cyclic loading during electronic device services and thermal shock in some extreme conditions and manufacturing processes. Accelerated testing methodology and the factors of accelerated testing are illustrated in terms of fatigue life of solder joints under various accelerated test conditions. As input for strain-based and energy-based life prediction approaches, the accurate calculation of inelastic strain range and inelastic strain energy density by constitutive models during thermal fatigue is critical for fatigue life prediction under different thermal fatigue conditions. Accordingly, the methodology of constitutive modeling for thermal cyclic loading is necessary to be addressed. The solder joint reliability assessment of the Ford joint specimen, PQFP, and Flip Chip packages are selected to illustrate the points addressed in this paper, based on Finite Element analyses. The comments and recommendations for future research are also provided for the readers.

2. Life Prediction Methodology

Approaches of fatigue life prediction are developed based on experimental stress/strain/energy data from thermal/mechanical cycling tests. A number of life prediction approaches have been proposed for solder joint fatigue during the past few years. These approaches can be classified into four categories: (i) strain-based approach; (ii) energy-based approach; (iii) fracture mechanics-based approach; and (iv) damage evolution-based approach. Stress-based approach is less used in practice although it can be useful for vibration or physically shocked or stressed components[6,15].

The definition of fatigue failure of a solder joint plays a critical role in understanding the above approaches and the validity of each approach. Basically, the fatigue failure is comprised of the initiation of a macroscopic crack and the propagation of the crack. The initiation of a macroscopic crack occurs at microscopic material level. The very ductile materials such as solder alloys are damaged by the micro-processes of void nucleation on phase and/or grain boundaries, void growth, and their coalescence to result in a macroscopic crack initiation[15-18]. It is believed that the irreversible inelastic deformation, including both plastic and creep strains, is the driving force of micro damage processes. This is the origin of the strain-based approach. On the other hand, the energy-based approach presents a kind of combination of strain-based and stress-based approaches. Clearly, the approaches only predict the fatigue life of a solder joint until the appearance of a macroscopic crack.

On the other hand, the propagating mechanism of the crack inside a solder joint under cyclic loading is controlled by fracture quantities. Therefore, the fracture mechanics-based approach predicts only the part of fatigue life when a macroscopic crack propagates through the solder joint to cause its electric and/or mechanical failure.

There are, in fact, wide discrepancies on the failure definition due to fatigue crack initiation and propagation in literature. For instance, expedient fatigue failure criteria 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. The predicted fatigue life, therefore, also depends on the definition. 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[6, 18].

Damage evolution-based approach, combining with Finite Element technique, is able to predict both parts of fatigue lives due to crack initiation and propagation[19], which is beyond the scope of the paper. Figure 1 illustrates the scopes of the different approaches for fatigue life prediction. Details of the methods and their mathematical formula are described in following sections.

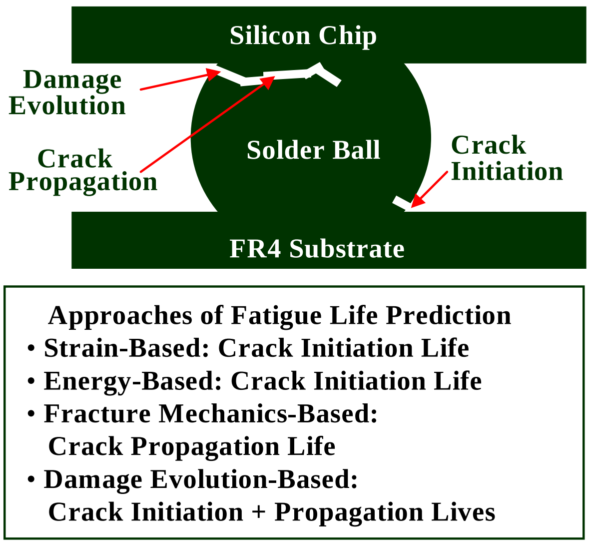

Figure 1. Illustration of life prediction methodology.

2.1. Strain-Based Approach

The well-known Coffin-Manson equation is inelastic strain range-based method for low cyclic fatigue[20,21]. The method has been widely used for fatigue life prediction of many solder alloys subjected to shear strain-dominated deformation[18,22]. There is a survey of many fatigue models available in literature[5,6]. The models are, in fact, based on the Coffin-Manson equation. Extending original one-dimensional form (1a) to three-dimensional form (1b) for solder alloys, the Coffin-Manson equation is given by,

$$(N_f)^{\beta}\,\Delta\gamma^{p} = C^{p} \tag{1a}$$

$$N_f = C^{I}\left(\Delta\varepsilon^{I}_{Mises}\right)^{-\alpha} \tag{1b}$$

with

$$\alpha = \frac{1}{\beta}\ , \quad C^{I} = \left(\frac{C^{P}}{\sqrt{3}}\right)^{1/\beta} \tag{1c}$$

where b is called the fatigue ductility exponent, and C^p the fatigue ductility coefficient. Dc^p and De$^I_{Mises}$ are the ranges of plastic shear strain and viscoplastic Mises strain, respectively. N_f is the fatigue life that is usually taken as the life of 50% load drop of a test specimen[18]. In order to account for frequency effect, a frequency-modified version of the Coffin-Manson equation was also proposed[20]. It was found[23], that between –50°C and 125°C, the life of isothermal fatigue tests of 60/40 solder can be approximated by a single Coffin-Manson expression with material constants b=0.51, C^p=1.14, at a constant frequency 0.3Hz. Therefore, a = 1.96, C^I = 0.4405 are obtained from Equation (1c). Material constants used in this paper for eutectic solder joints subjected to thermal fatigue between –40°C and 125°C are listed in Table 1.

Table 1. Material constants for 60/40 solder fatique.

α	C^I	δ	C^E
1.96	0.4405	1.818	347.55

It should be pointed out that Equation (1b) must be used for the life prediction of solder joints in 3D deformation states. The correct identification of the De$^I_{Mises}$ from 3D Finite Element calculation will be shown in later section for thermal cyclic loading. There is, however, some confusion in the literature for the identification. Moreover, inelastic Mises strain range is only input quantity of the Coffin-Manson equation, which actually separates the life calculation with the deformation computation that is the task of constitutive modeling.

On the other hand, a more sophisticated method[24] for creep-plasticity interaction is the Strain Range Partitioning (SRP) technique. Rate-independent plastic and rate-dependent creep strains are separated by a special procedure for each cycle. Some applications of the SRP method to solder alloys and a modified version of the SRP technique can be found in References[1,18].

It is well known that the nonlinear viscoplastic property of solder alloys is highly rate/temperature-dependent[1,2,15,18,19]. The critical question is then how to define the rate-independent plastic curves from the experimental data. In literature, however, quite different curves have been used as rate-independent plasticity for eutectic solder. The real rate-independent curve at a specific temperature might not be reached actually by any test machine, which will be required to run a tensile test at a strain rate as low as 1.E-10/s to find out truly the rate-independent property for a solder alloy. Another expedient definition of plasticity can be the tensile strain/stress curve at a relatively high strain rate, about, 1.E-1/s. On the other hand, solder joints of an electronic package during temperature ramping stage, in fact, are subjected to continuous change of strain rates. Therefore, any particular choice for the plasticity curve at a specific tensile strain rate cannot be suitable for and consistent with the whole ramping stage of thermal cyclic loading. There is always the time-dependent deformation, creep strain, during thermal cyclic loading.

Considering the difficulty and confounding of obtaining pure rate-independent plastic deformation from highly rate-dependent viscoplastic strain of a solder alloy, the SRP method is not recommended in this paper. Using the Coffin-Manson equation by the ranges of plastic strain and creep strain, respectively, for life prediction, is not recommended either. Instead, the range of time/rate/temperature dependent viscoplastic Mises strain that unifies plastic strain with creep strain is strongly recommended to be used for life prediction in Equation (1b).

2.2. Energy-Based Approach

Recently, strain energy-based methods have been applied to the fatigue of solder joints[18,25], to name a few. Actually, the method was used very early[26]. A similar power-law relationship of the Coffin-Manson equation in terms of inelastic hysteresis energy density, W^I , is written as follows,

$$N_f = C^E \left(W^I\right)^{-\delta} \qquad (2)$$

where d and C^E are the material constants. It was reported[27] that d=1.818 and C^E =347.55 for the 60/40 solder isothermal fatigue between –50°C and 125°C. These constants are also listed in Table 1. The unit of W^I has been transferred to mm-N/mm^3 for convenience. It should be pointed out that some authors in literature have interpreted the term of inelastic strain energy density W^I in their papers instead of inelastic or plastic strain energy. This can result in some confusion in using Equation (2) and calibrating material parameters.

Similar to the SRP method, the energy density partitioning approach has been proposed[28]. Total strain energy density can be divided into elastic, plastic, and creep strain energy density in each cycle. The relationship of each component of the energy density with fatigue life has been assumed to follow a Coffin-Manson power-law relationship such as Equation (2). Total creep-fatigue damage then follows the Miner's linear superposition rule. However, the same argument about the difficult separation of creep and plastic strains for the SRP method could be true for the application of the strain energy density partitioning approach. From this point of view, the total inelastic energy density-based approach seems favored for the life prediction of thermal fatigue.

The energy approach does have its technical merit for three-dimensional deformation states[28]. The extended Coffin-Manson, Equation (1b), is also convenient for application to three-dimensional deformation states. In fact, the ranges of inelastic Mises strain and inelastic energy density are only two suitable quantities for thermal fatigue life prediction of solder joints, based on Finite Element analysis.

There is, however, a complication that must be addressed when utilizing W^I for life prediction[27,29]. Moreover, fatigue life was not found to be a single valued function of the hysteresis energy density for changing frequency tests[27,29]. The authors of the paper have also identified the questionable tendency of predicted fatigue lives by the energy-based approach for accelerated testing via frequency change, as shown in later sections. The similar result was also reported in Reference[13].

2.3. Fracture Mechanics-Based Approach

For the large solder joint structures such as SMT (Surface Mounting Technique) LCR (Leadless Chip Resistor) solder joints, the fatigue life of crack propagation from a tiny crack to final joint failure electrically and/or mechanically can be a significant portion of whole fatigue life. Therefore, fracture mechanics approaches may play an important role in characterizing the crack behavior and thus can lead to the formulation of life prediction methods for such joints. Details can be found in References[30,31].

3. Accelerated Testing Methodology

The accelerated testing is a very important industrial practice for package design and rapid reliability assessment. The qualification and reliability tests of advanced packages such as BGAs will take 3000 to 15000 cycles to reach failure typically. The time to failure is about 4 to 10 months at 1-2 cycles/hour. It is a time-consuming process in addition to purchasing expensive test equipment. The accelerated testing method is to shorten the time to failure by over-stressing solder joints. The utmost goal is to run the qualification and reliability tests by developed computer tools. The test procedure is realized currently in electronic industries by rising extreme temperatures, shortening dwell time, and increasing temperature ramping rates. The accelerated testing methodology, actually, is closely related with the methodologies of fatigue life prediction and constitutive modeling. Acceleration factors and their bounds can be determined by integrating a fatigue life prediction approach with a powerful viscoplastic model that is able to be used for the investigation of various accelerated conditions. It is still not certain on how to determine the accelerated testing factor and how to correlate fatigue life of accelerated tests with product/package life during service conditions[2,32]. Until the present time, little systematic research works are reported.

3.1. Failure Modes via Accelerated Testing Bounds

It is very important that proper considerations are given to failure mechanisms and modes when designing an accelerated test for solder joint reliability assessment. A life prediction method can be very useful tool if it can predict failure modes of solder joints and embed the dominating failure mechanisms such as intergranular or transgranular cracking, grain boundary sliding, and grain growth-induced shear banding.

There will be the bounds of accelerated factors regarding to failure mode change or thermal gradient limitation under extreme accelerated test conditions. For instance, the increase of ramping rate to that of thermal shock may induce the failure mode change from intergranular fracture of solder joints to underfill delamination of Flip Chip packages and failure location shifting. Details will be discussed in later sections.

3.2. Isothermal Fatigue via Thermal Fatigue

One related issue of accelerated testing is the relationship between isothermal and thermal fatigue. Isothermal fatigue can be performed much faster than thermal fatigue since it is an easier experiment to operate under well-controlled laboratory testing conditions. It is often used to calibrate constitutive models and the methods of fatigue life prediction. Electronic industries have been accumulating reliability testing data of thermal fatigue of electronic packages[6,7,33]. Isothermal fatigue and thermal fatigue exhibit a number of similarities and differences[15]. However, the mechanisms of deformation and failure include an effect in thermal fatigue that can be absent in isothermal fatigue. Accelerated testing can also create new failure modes, as discussed above. The microstructure evolution occurs in near eutectic solders in thermal fatigue[2,34]. Temperature cycle can induce solder recrystalization and then grain growth. In fact, the strain rate keeps changing during thermal cyclic loading due to the temperature dependence of viscoplastic behaviors of solders. The mean strain/stress and energy density generated during the initial ramping or cooling stage of thermal cycling are also an important factor for thermal fatigue life, which has been ignored for investigation at isothermal fatigue tests. Therefore, strain rate and temperature history, microstructure evolution, and mean strain/energy density are three additional factors that need to be evaluated for constitutive modeling, fatigue life prediction, and accelerated testing for the thermal fatigue of solder joints.

4. Constitutive Modeling Methodology

As discussed in above sections, the life prediction of solder joints under creep-fatigue interaction is still a difficult problem in terms of crack initiation and crack propagation. Constitutive modeling is one of the keys to account for viscoplastic property of solder alloys and compensate for the deficiency of life prediction model by strain and energy-based approaches. The range of inelastic Mises strain or strain energy density must be accurately calculated by Finite Element analysis, based on a realistic and elaborated nonlinear constitutive model of solder alloys. The effects of extreme temperatures, temperature ramping rates, dwell time and temperature, and solder microstructure on thermal fatigue life under accelerated test conditions can be explored only by powerful constitutive models that incorporate into the effects of time/temperature/rate, deformation and temperature history, and microstructure evolution.

4.1. Separated Modeling via Unified Modeling

Currently, the constitutive models of solder alloys, used in electronic packaging, are mostly separated as rate-independent plasticity and steady-state creep[1,2,35,36]. Classical plastic flow theories and power-law creep are still widely used. The corners and interfaces of solder joints under thermal shock and accelerated test conditions can reach the regime of power-law breakdown. The major deficiency of separated-models is the lack of predictive power to correctly describe the stress/strain hysteresis curve during thermal cyclic loading. The separated constitutive models are also lack of ability to investigate the effects of heating/cooling rate changing. The inaccuracy of the hysteresis curve calculation substantially magnifies the error of fatigue life prediction of solder joints due to the power-law dependence of fatigue life on the ranges of inelastic strain and energy density according to Coffin-Manson equation. On the other hand, unified constitutive modeling considers plastic strain and creep strain as an inelastic strain. The approach has been developed since the 1970's for the design and reliability assessment of structures and parts made from super alloys served at high temperatures[37-39]. The alloys exhibit the similar deformation behaviors at high temperatures as those of solders even at room temperature. Due to its intrinsic merit of unified constitutive modeling for rate/ time/ temperature-dependent nonlinear properties of solder alloys, it is strongly recommended in this paper for solder joint reliability assessment.

4.2. Viscoplasticity with Damage Evolution

New advances in this area have been achieved, including the application of unified viscoplastic constitutive models to solder alloys[34,40-43]. The unified viscoplasticity with damage evolution is proposed for the fatigue life prediction of solder joints[19,44,45]. In addition, cyclic hardening/softening, microstructure evolution, and scale effect have been also incorporated into the constitutive framework[19,45] that also covers both power-law and power law breakdown regimes. The implementation of the framework into such commercial code as ABAQUS has been used to calculate hysteresis curves and predict thermal fatigue life at critical points, interfaces, and corners for Flip Chips and BGAs[9,45]. The new methodology of fatigue life prediction, based on unified models incorporating into damage evolution and crack/failure criteria, can be developed. By the local approach to fracture, the fatigue life of solder joints during both crack initiation and crack propagation can be predicted by Finite Element techniques.

5. Solder Joint Reliability via FEA

Several examples performed by ABAQUS Finite Element analysis (FEA) are presented as follows, to illustrate the significance of solder joint reliability assessment and highlight the points discussed above.

5.1. Life Prediction of Ford Joint Specimen

The Ford joint specimen[2,46] is selected as a typical example to perform parametric studying under accelerated testing conditions since the joint specimen is mainly subjected to shear deformation and well calibrated by experimental data and Finite Element calculation. The geometry of the specimen and its Finite Element meshing are shown in Figure 2 (a) and (b). The specimen is composed of an aluminum beam and an alumina beam which are soldered together by the solder joint. The aluminum and alumina are modeled as thermal elasticity whereas solder alloys as rate-dependent plasticity. All data of the materials are taken from References[2,46].

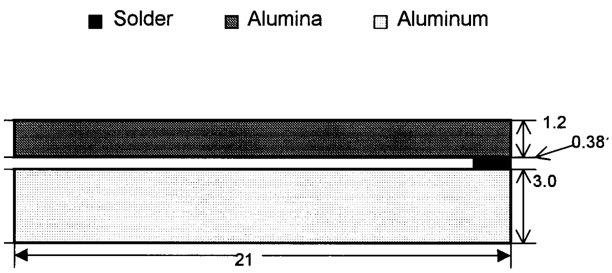

Figure 2(a). Dimensions of Ford joint specimen.

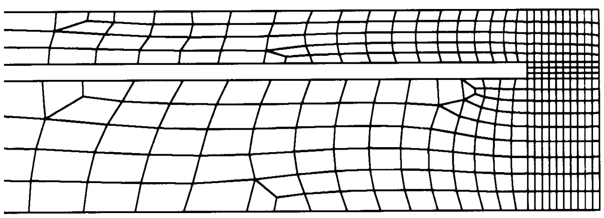

Figure 2(b). 2D Finite Element meshing of the specimen.

Figure 3 shows a FEM result that reasonably agrees with experimental data and is totally identical with the FEM analysis data by user-defined subroutine for the same temperature profile[2,46]. Therefore, the Finite Element technique of rate-dependent plasticity in ABAQUS adapted in this paper is verified to effectively model the viscoplastic behaviors of solder alloys. The details can be found in Reference[9]. The isotropic hardening of solder alloys is assumed in this work.

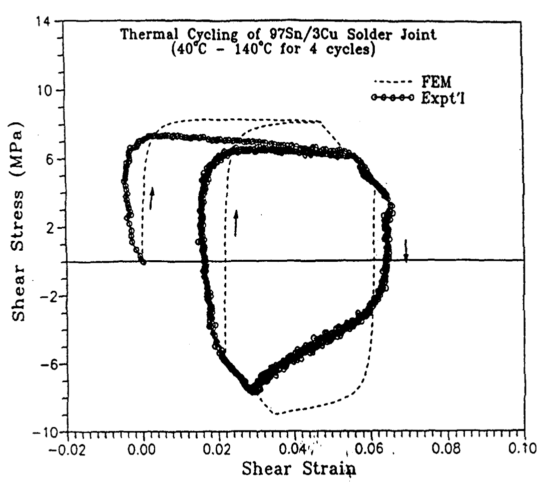

Figure 3. Comparison of FEM calculation with experimental data for thermal cyclic loading.

Although this solder joint is well designed for pure shearing, there is unavoidable bending near the corners of the joint. Therefore, the range of inelastic shear strain can be different at different joint locations.

Corner elements 3, 7, 26, 30 and the middle element 13 on the joint cross section are selected, respectively, to investigate the effect of non-uniformity of the joint deformation, as shown in Figure 4(a). The inelastic strain ranges of the elements under the temperature profile (see Figure 4(b)) are shown in Figure 4(c), which is calculated as a plane stress analysis. Based on the Coffin-Manson Equation (1b) and material constants in Table 1, predicted fatigue lives of five elements are shown in Figure 5 with different dwell time. The longer the dwell time, the shorter the fatigue life, due to creep damage accumulation during dwell period. Although the bending effect is not significant, the cycles of fatigue life at different locations of the joint are substantially different, see Figure 5.

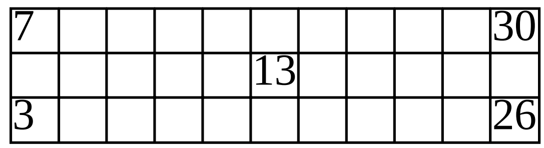

Figure 4(a). Locations of five elements of the joint.

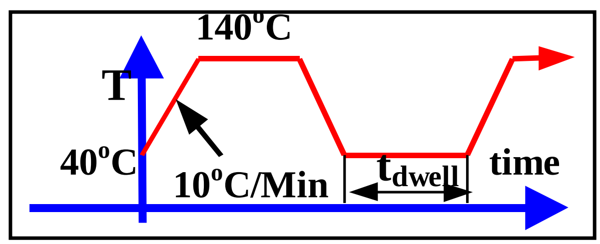

Figure 4(b). Applied temperature profile.

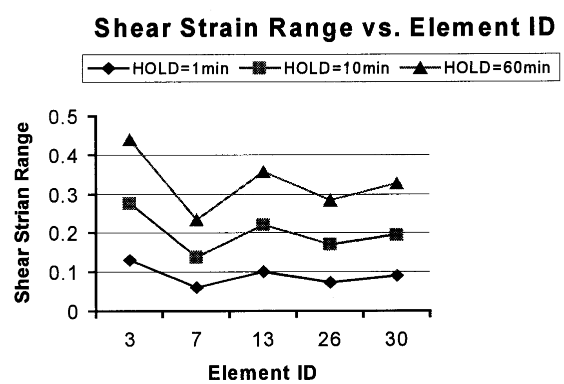

Figure 4(c). Ranges of inelastic shear strain of five elements with different hold time periods.

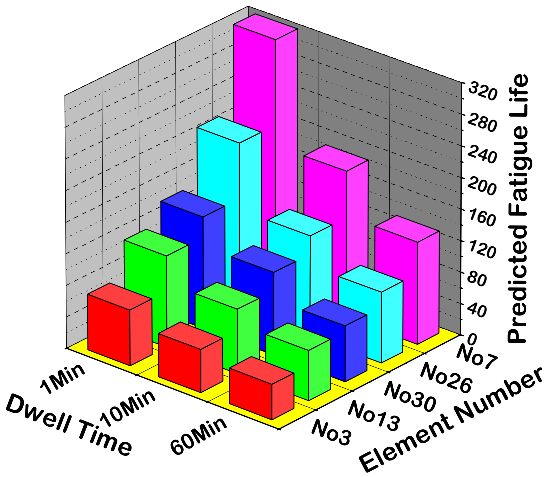

Figure 5. Predicted fatigue lives of five elements.

This fact can be used to propose bound concept for the fatigue life of a solder joint, depending on the failure criteria and failure locations. Calculated fatigue life at the position where maximum range of inelastic strain is located will be a conservative lower bound that presents the shortest fatigue life of the joint and indicates a macroscopic crack initiation of the solder joint. In the case of the Ford joint specimen, the lower bound of its fatigue life at element 3 and the upper bound of the life at element 7 have been predicted due to the non-uniformity of shear deformation. The strain of middle element 13 gives the average value over the joint. Correspondingly, calculated fatigue life at element 13 is indeed between two bounds. Alternatively, using the average range of inelastic strain or the average of inelastic strain energy density[47] over a solder joint will predict a fatigue life within bounds. Therefore, the concept of fatigue life bound gives a clear margin for solder joint reliability assessment.

5.2. Accelerated Testing: Insights from Life Prediction

In principle, the Coffin-Manson equation predicts the fatigue life of the solder joint on the material level, which indicates the material element located at maximum inelastic strain range or energy density reaches the failure criterion. In terms of damage mechanics [19,48], it is known that so-called tri-axial stress ratio, that is, the average stress of three principal stress components over the Mises stress, accelerates damage evolution and crack initiation. The effect thus shortens the fatigue life at the corners of the solder join where the solder material element is always subjected to three dimensional stress states. Therefore, it is necessary to distinguish physical accelerated factor at the material level from geometrical accelerated factor at structural level for joint reliability assessment. Accelerated testing actually accelerates both factors simultaneously. Moreover, the physical accelerated factor can be determined by testing solder material samples. The geometrical accelerated factor must be determined by performing Finite Element analysis, depending on the shape and size of solder joints.

Figure 5 shows that the average accelerated failure factor at each element is around 2.0 for dwell time from 1 minute to 60 minutes for the joint specimen. The geometry-induced local failure has an accelerated factor around 3 to 4.5. It is defined by the ratio of N_f at element 7 over N_f at element 3. The factor decreases with the increase of dwell time since creep during dwell time causes the uniformity of deformation within a solder joint.

In order to investigate how the accelerated failure factor is amplified by accelerated test conditions, a set of special virtual tests via FE analysis was designed under different ramping rates without dwell time. Extreme temperatures were selected as 125°C for maximum and –40°C for minimum. The ramping rate, that is, both heating and cooling rate in this case, was changed from 0.5°C to 600°C per minute, as shown in Figure 6. The ramping frequency is defined as the inverse of one cycle time taken at heating and cooling. Figure 6 shows shear stress/strain curves of middle element 13 at three typical ramping rates of 1°C/min, 10°C/min, and 100°C/min, respectively. Maximum magnitudes of shear stress increase with the increase of ramping rates, indicating viscoplastic deformation characterization. On the contrary, the ranges of inelastic shear strain significantly decrease with the increase of ramping rates. It is pointed out that only rate-dependent constitutive modeling can predict the stress and the strain characterization under different ramping rates. The rate-independent plasticity or creep laws are not able to obtain this kind of mechanical response.

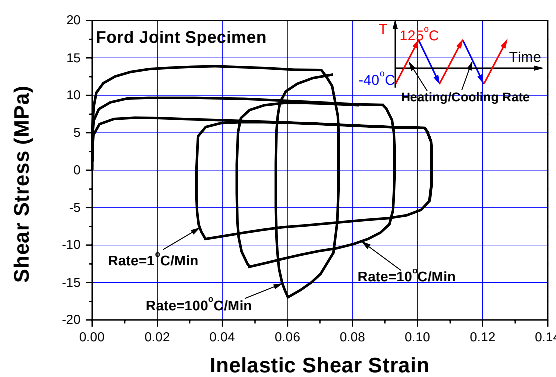

Figure 6. Shear stress/strain curves under accelerated tests with different ramping rates.

Figures 7 and 8 show how to calculate the ranges of inelastic Mises strain and inelastic strain energy density from the accumulated curves of the quantities with temperature cycles. It should be noted that the inelastic strain is accumulated twice per cycle. Moreover, the inelastic strain or energy generated during first heating or cooling stage is relatively large but it does not contribute to the range calculation whereas it directly contributes to the calculation of mean strain or energy, see Figure 6. From Equations (1) and (2), the fatigue life can be predicted based on the calculated ranges of inelastic Mises strain and strain energy density. The results are presented in Figure 9 illustrating the fact that the faster the ramping frequencies, the longer the fatigue life for strain-based approach.

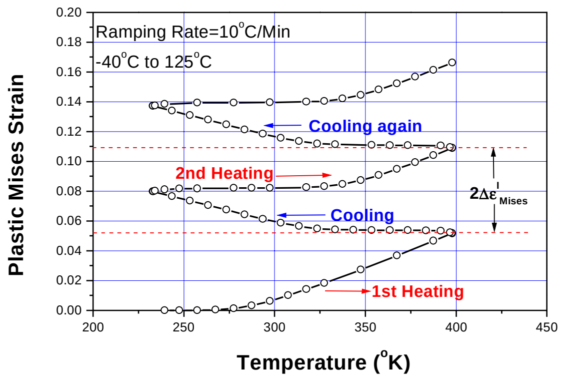

Figure 7. Calculation of inelastic strain range.

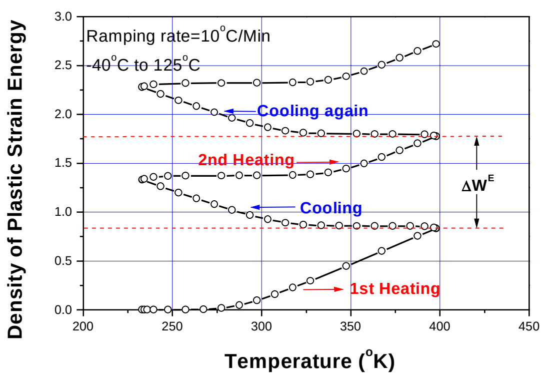

Figure 8. Calculation of the range of inelastic strain energy density.

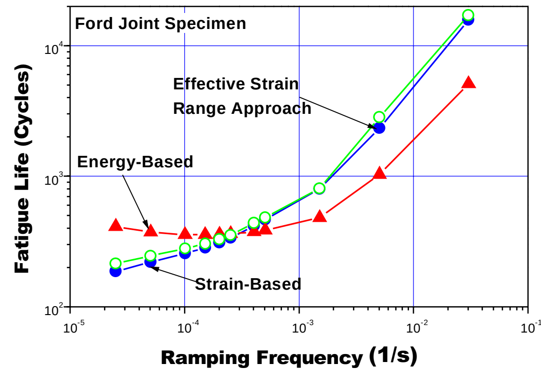

Figure 9. Fatigue life prediction via different approaches.

However, the energy-based approach predicted a questionable tendency at low ramping frequencies and slow ramping rates. At very slow ramping rates, energy-based approach predicts almost the same fatigue cycles. The reason of this phenomenon comes from the rate-dependent behavior of solder materials. When the ramping rate is decreasing, the stress decreases but the strain range increases. Inelastic strain energy density at low range of frequencies, therefore, is not changed significantly. If the energy density is divided by both the maximum stress and a factor 2, an effective strain range thus is obtained. Predicted fatigue life based on the effective strain range approach is almost the same as that from strain-based Coffin-Manson equation, as shown in Figure 9. The example shows that the energy density might be not a proper quantity for fatigue life prediction under some accelerated test conditions such as different ramping rates. In fact, it was found the energy density predicted wrong tendency of fatigue life for fatigue tests under different frequencies [27,29].

The effect of dwell time has been investigated in a similar way, keeping the same ramping rate of 10°C/min and changing the dwell time from 1 minute to 600 minutes. Figure 10 shows that the lives predicted from the energy-based approach are quite close to those from strain-based approach for such type of accelerated testing. Furthermore, Figure 11 shows that life cycles decrease exponentially with the increase of the time of one cycle. Therefore, the time to failure, that is, the total test time of one sample, can be a proper parameter to measure accelerated factor.

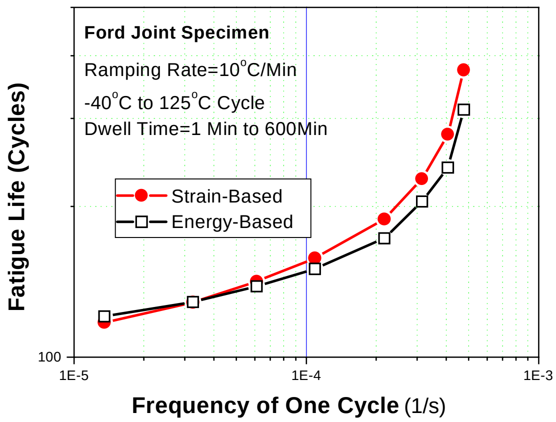

Figure 10. Fatigue life with different dwell time.

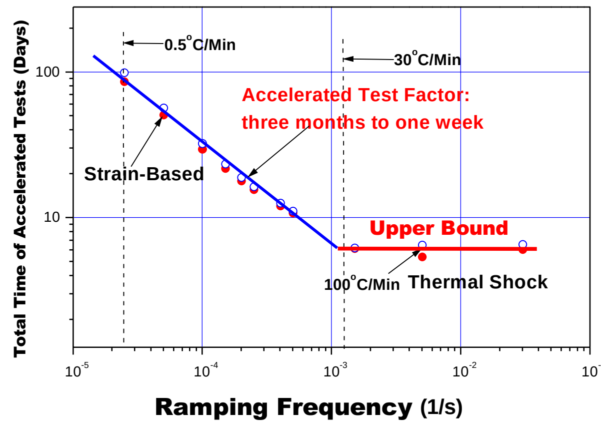

Figure 12. There is an upper bound for accelerated testing.

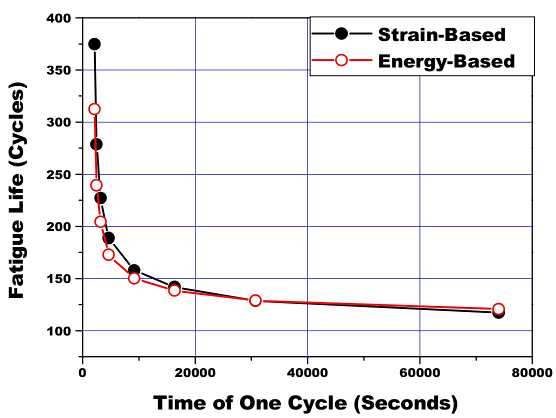

Figure11. Fatigue life with the time of one cycle.

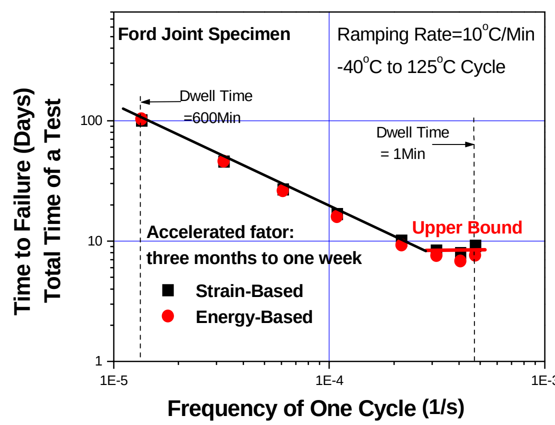

Figure 13. Accelerated testing factor via reducing dwell time.

The time to failure can be calculated by multiplying fatigue cycles by one cycle time. When the data of the time to failure were plotted against ramping frequencies, a surprising curve was obtained, as shown in Figure 12 for changing the ramping rate, and Figure 13 for changing the dwell time. There is an upper bound for accelerated testing, in addition to a linear relationship in double logarithmic coordinate system.

The significance of this result indicates that it is not necessary to accelerate fatigue test to equipment limitation. The fastest test will take about one week for both accelerated methods. For the joint specimen and extreme temperatures chosen, the total time of accelerated tests could be shortened from three months to one week that is the shortest period for a thermal fatigue test. Maximum ramping rate is about 30°C/min in this case whereas shortest dwell time is about 15 minutes. These results are really meaningful to industry practices for the design of accelerated testing. If one wants to run accelerated thermal cyclic test of an electronic package less than one week, the alternative method must be used. For instance, isothermal mechanical fatigue with meaningful test procedure[49] can be a fast process for solder joint reliability assessment of BGAs.

5.3. Fatigue Life Prediction of a PQFP Package

A PQFP package was chosen to illustrate the importance of using unified or rate-dependent constitutive model for the methods of strain-based and energy-based life prediction. A typical PQFP package and its 2D Finite Element model are shown in Figure 14, and Figure 15(a) with local amplification of a solder joint, respectively.

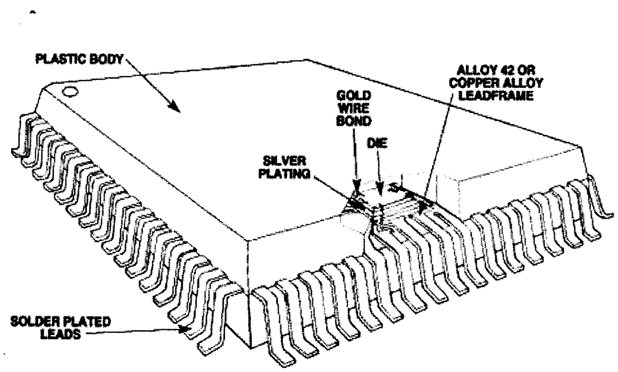

Figure 14. A typical PQFP package.

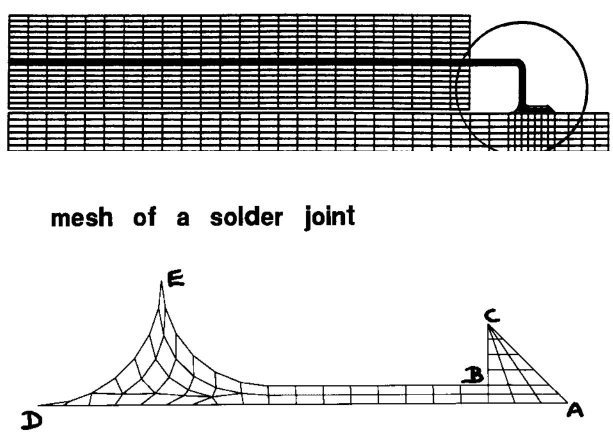

Figure 15(a). 2D Finite Element model of the PQFP.

The size of the package is the same as that used in Reference[47]. The solder material data were taken from experimental tests[2]. The thermo-mechanical material data of chip, FR-4, copper lead, and molding compound were taken from CINDAS database[50]. The shear stress/strain curve at point A, the toe of a solder joint, under the thermal cyclic loading with applied temperature profile in Figure 15(b) is shown in Figure 16(a). Moreover, the cyclic ratcheting was also predicted. This shows that there is a relatively large amount of mean shear strain that increases step-by-step with the increase of thermal cycles. Its effect on fatigue life needs to be explored for both experimental and theoretical studies in the future.

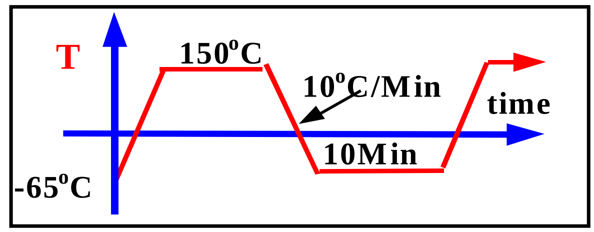

Figure 15(b). Applied temperature profile.

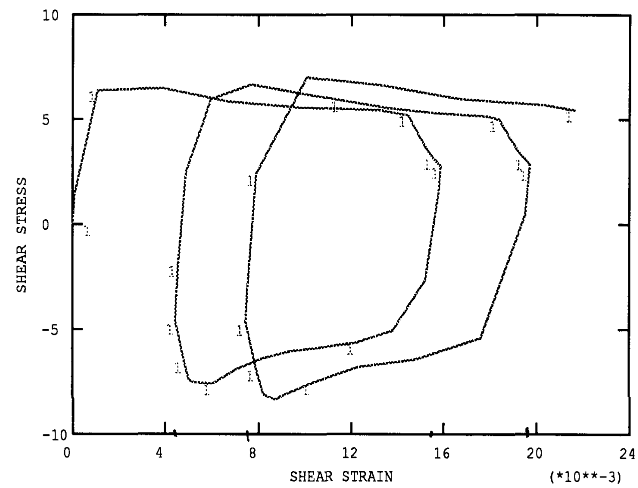

Figure 16(a). Shear stress and shear strain at toe a calculated by unified constitutive modeling.

Figure 16(b) shows the result of equivalent stress/strain curve calculated by separated constitutive modeling, which is taken from Reference[35] for a similar PQFP package at the same location of the solder joint. Although slight different solder data were used to calculate Figures 16 (a) (b), qualitative difference in terms of shape of two hysteresis curves is significant due to totally different constitutive modeling methods. This comparison illustrates the importance of correctly using the rate-dependent constitutive modeling to calculate hysteresis curve. The significant difference in the calculation of strain energy density and inelastic strain during thermal cycling could produce a substancial difference in the fatigue life prediction due to the power-law characterization of Coffin-Manson Equations (1) (2).

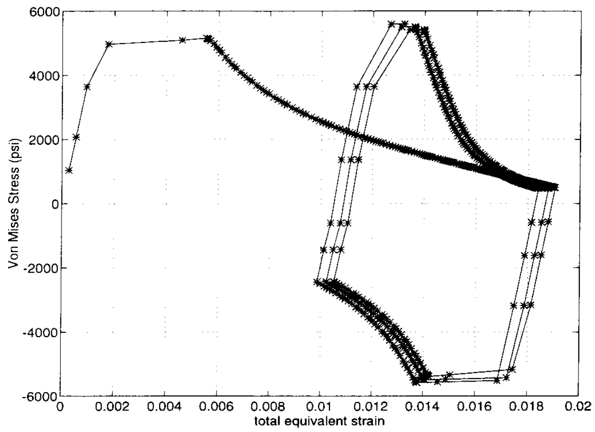

Figure 16(b). Shear stress and shear strain at toe a calculated by separated constitutive modeling.

Another important issue has been ignored in literature concerning different 2D Finite Element modeling for the reliability assessment of solder joints. Figure 17 shows enormous differences in fatigue life prediction where different 2D Finite Element models were used. Actually, this situation exists in many reports of Finite Element modeling. The plane stress (PSS) model predicts shortest life, a lower bound. On the other hand, the plane strain (PSN) model predicts longest life, an upper bound. The life prediction based on axi-symmetrical modeling (AXI) is, as expected, between the two bounds. Therefore, considering the time and cost saving of running Finite Element modeling, 2D axi-symmetric modeling is recommended, at least, for rapid reliability assessment.

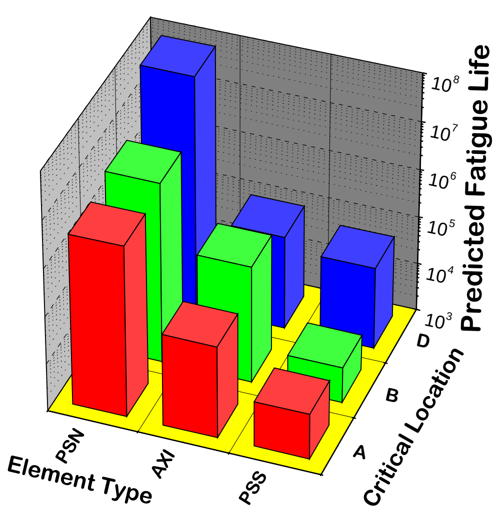

Figure 17. Fatigue life prediction via different 2D FEM models.

6. Life Prediction of Flip Chip Packages

Flip Chip packages become more important due to the development of potential chip-on-board technology and the successful utilization of underfill encapsulant. The fatigue life of solder joints of a Flip Chip can be extended tremendously[2,8,9,33,51,52].

Figures 18 (a) (b) show schematically Flip Chip packages with ball pitch size from 250 microns to 50 microns. The basic geometric dimensions of chip and FR-4 are the same as in Reference[53]. Instead of plane stress/plane model[53], axi-symmetrical 2D Finite Element has been selected as the geometric model. Over 4000 elements were used with the local fine meshing of solder balls, underfill corners, and interfaces. Currently, most of analyses still use thermal elastic properties of underfill encapsulants to perform Finite Element simulation of Flip Chip packages[54]. The reason can be attributed to the lack of experimental data of nonlinear properties of underfills. Consistent and systematic experimental data of underfill FP4526 have been generated by combining a 6-axis mini tester with well-manufactured thin strip specimen[55,56]. The nonlinear behaviors of the underfill have been explored in terms of temperature dependence of Young's modulus and CTE (Coefficient of Thermal Expansion), viscoelastic and viscoplastic properties[56]. The thermal-mechanical data of chip and FR-4 are taken from References[50,53]. The database is then incorporated into ABAQUS material model library with the nonlinear viscoplastic behaviors[19,56,57] of eutectic solder and underfill FP4526 for rate-dependent constitutive modeling[9,45]. All material constants for fatigue life prediction were taken from Table 1. With the implementation, the nonlinear Finite Element analysis of the Flip Chip package with ball pitch 250-microns has been verified by Moiré measurement for simple creep tests[53].

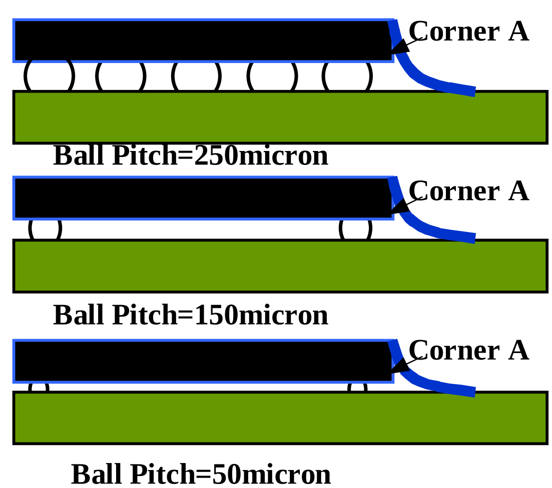

Figure 18(a). Schematic Flip Chips with different ball pitch sizes.

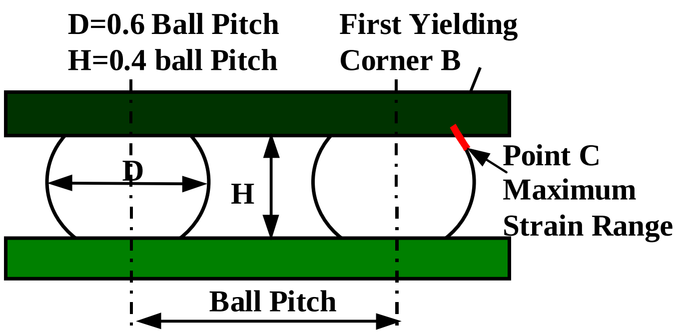

Figure 18(b). Ball size and critical point at outmost solder ball.

6.1. Fatigue Life Prediction With and Without Underfill

Deformation over a solder ball becomes more uniform due to the enhancement of the underfill encapsulant. The deformation mode of solder balls of a Flip Chip with underfill also changes from shear-dominated mode for a Flip Chip without underfill to more uniform and 3D deformation states due to different stress/strain boundary conditions around a solder ball. As a result, the range of inelastic Mises strain of outmost solder ball under thermal cyclic loading has been substantially reduced due to the underfill strengthening mechanism. Therefore, the thermal fatigue life of Flip Chip packages has been increased tremendously.

Nonlinear Finite Element analysis[9] showed inelastic strain localization inside the outmost solder ball of the Flip Chip package without underfill encapsulant. Therefore, early failure can be induced by the localized deformation as the initiation of cracks. Predicted failure location is very close to the corner B, as shown in Figure 18(b). Therefore, short fatigue life has been predicted. Calculation also indicated that inelastic strain distribution becomes much more uniform in the underfilled Flip Chip inside every solder ball. The underfill indeed transfers the shear deformation from one ball to another. Moreover, the critical point of the Flip Chip package with the underfill is also shifted from the corner B of outmost solder ball to the interface C between the solder ball and the underfill, as shown in Figure 18(b), which matches qualitatively the experimental observation of crack initiation[58].

The Flip Chip was subjected to thermal cyclic loading from –40°C to 100°C with the ramping rate of 10°C/min and the dwell time of 10 minutes. For the Flip Chip without underfill, predicted life cycles, based on inelastic shear strain range and Mises strain range, respectively, are very close to each other due to shear dominated deformation. In the case of Flip Chip with underfill, the range of inelastic Mises strain must be used for life prediction due to 3D-deformation states. The fatigue life due to underfill strengthening mechanism increases roughly ten times for the Flip Chip package, as summarized in Table 2.

Table 2. Fatigue life of Flip Chip with/without underfill.

Flip Chip	Without Underfill		With Underfill
Inelastic Strain Range	$\Delta\gamma^{I}$	$\Delta\varepsilon^{I}_{Mises}$	$\Delta\varepsilon^{I}_{Mises}$
	0.0429	0.02293	0.00732
Fatigue Life (cycles)	618	720	6758

6.2. Life Prediction of Flip Chips without Underfill via Unified and Separated Constitutive Modeling

In this case, the Flip Chip without underfill is equivalent to a type of BGA package. In order to compare separated with unified constitutive modeling, a special design loading paths is shown in Figure 19. During separated modeling, approximate temperature profile[28] has to be adopted to match industrial thermal cyclic profile. Due to the difficulty of calculating the rate/time-independent plastic strain during temperature ramping, the approximation procedure of applying temperature was taken as jumping to extreme temperatures as plasticity and followed by creep during a dwell time which is equal to the temperature ramping period[28,35], as shown in Figure 19. Many authors used similar procedure to calculate the stress/strain hysteresis curves during a temperature ramping stage, based on separated constitutive modeling. Therefore, five paths were selected for unified constitutive modeling by changing temperature ramping rates from 6°C/min to 6000°C/min (as virtual plasticity), whereas the time of one-cycle and extreme temperatures are kept unchanged, as shown in Figure 19. As expected, the separated modeling will predict the same results for all loading paths.

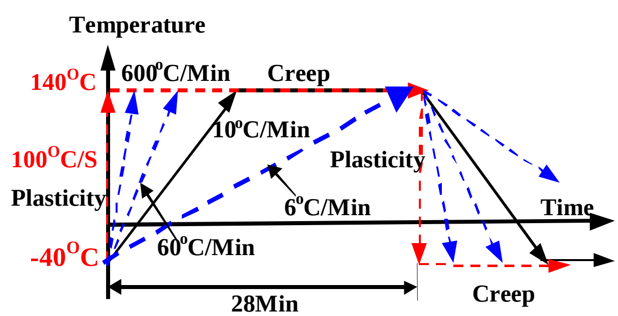

Figure 19. Path-dependence of shear stress/strain curves via unified constitutive modeling.

On the other hand, since nonlinear property of solder alloys is highly rate/time/temperature-dependent, in literature, authors have used quite different curves as plasticity for eutectic solder, lacking clearly consistency and uniqueness. Three tensile curves[40] at the strain rates of 1.67E-2/s, 1.67E-3/s and 1.67E-4/s were taken as rate-independent plastic definition at the temperatures of -55°C, -35°C, -15°C, 22°C, 50°C, 75°C and 125°C, respectively.

The hyperbolic law of creep with the same material constants used in Reference[53] was applied to calculate the creep deformation. All stress/strain curves are plotted at the corner B of outmost solder ball. Figure 20 shows that the strain range of plastic plus creep deformation is shifted with the increase of mean strain when the tensile stress/strain curve at higher strain rate was used. Therefore, the predicted fatigue life is almost the same if strain-based approach is used. However, the density of strain energy significantly increases for higher rate case. The 40 percent difference of predicted fatigue lives by energy-based approach was found among the three cases.

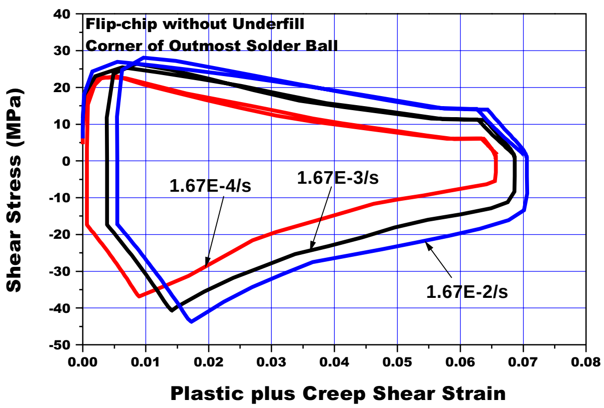

Figure 20. Shear stress/strain curves via separated constitutive modeling.

Figure 21 shows shear stress/strain curves at the corner B of the outmost solder ball, obtained by unified constitutive modeling for planned four loading paths. Inelastic shear strain range increases with the increase of ramping rates. Qualitative difference of hysteresis curve shape can be found by comparing Figure 20 with the curve of 6000°C/min (100°C/s, virtual plasticity) path in Figure 21 by unified modeling. The curves in Figure 21 match qualitatively nonlinear characterization measured experimentally by solder joint specimens subjected to thermal cycling[2]. Clearly, inelastic shear strain was generated mainly during heating and cooling stages. The inelastic energy density, however, is very sensitive to temperature ramping rates. In terms of fatigue life prediction, the 400 percent difference of fatigue lives among the four cases has been predicted based on energy approach. Although these findings need to be verified by well-designed accelerated tests, the conclusion is that strain-based life prediction approach is most likely combined with separated constitutive modeling to surpass its intrinsic deficiency. In contrast, energy-based life prediction approach could mislead the results obtained by unified constitutive modeling. The combination of energy-based approach with separated constitutive modeling could result in significant scatter of life prediction data, therefore, is not recommended in this paper.

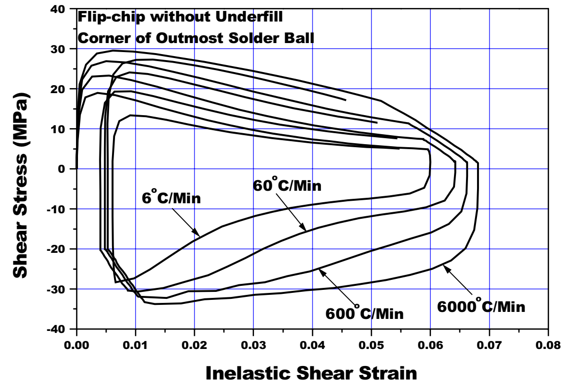

Figure 21. Path-dependence of shear stress/strain curves via unified constitutive modeling.

6.3. Life Prediction of Flip Chips Under Accelerated Testing

Accelerated testing conditions with the same dwell time of 10 minutes and different ramping rates from 0.3°C/min to 600°C/min have been applied to the Flip Chip package of 50-micron ball pitch under thermal cycling from –40°C to 125°C.

Figure 22 shows predicted fatigue lives against ramping frequencies. The energy-based approach produced questionable life prediction for this kind of tests, as pointed out earlier. A logarithmic linear relationship of the time to failure was obtained by strain-based approach, as shown in Figure 23. The time-to-failure of accelerated testing for the Flip Chip package can be reduced from three years to one week. An upper bound was not reached by current analysis. Alternatively, the upper bound can be considered from coupled thermal-mechanical analysis[59] by temperature gradient inside a real Flip Chip package. When the ramping rate is too fast, for instance, in the case of thermal shock, the temperature gradient can be so large that accelerated thermal cyclic loading can change failure modes totally.

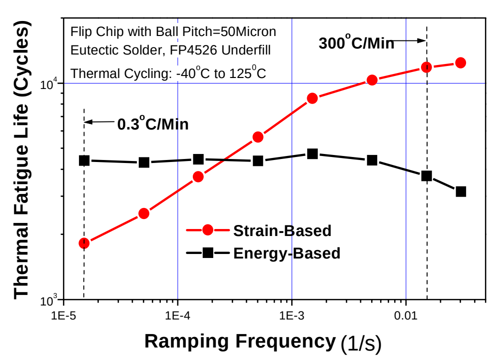

Figure 22. Fatigue life prediction of the Flip Chip under different ramping rates of thermal cyclic loading.

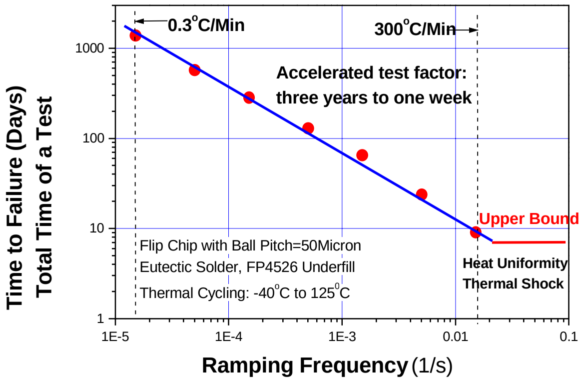

Figure 23. Accelerated testing factor by increasing ramping rates.

The details of the characterization of stress and strain at critical location C are shown in Figure 24 for accumulated Mises strain and Figure 25 for the normal stress/strain curve under the thermal cyclic loading. Compared with BGA-like Flip Chip without underfill (Figures 20, 21), the characterization of stress/strain curves are qualitatively different. In particular, mean inelastic strain is about half of the strain range in the previous case whereas mean inelastic Mises strain is greater than the strain range in later case. The effect of mean strain on fatigue life, in particular, for underfilled Flip Chip packages needs to be investigated.

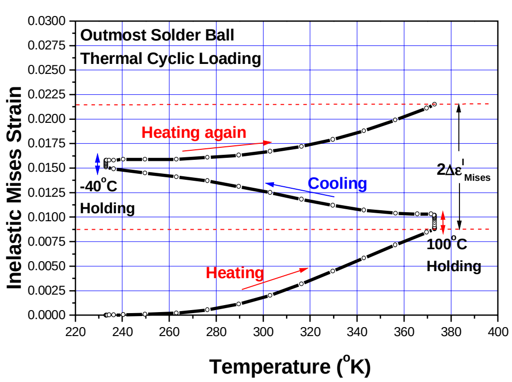

Figure 24. Accumulated inelastic mises strain with temperature cycling.

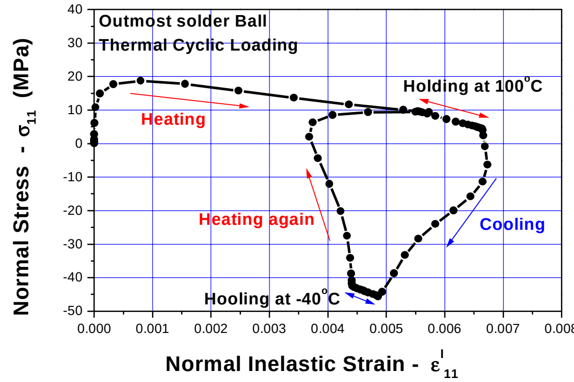

Figure 25. Curve of normal stress/strain at point C.

On the other hand, the corner A of the underfill side is a critical point for underfill delamination[60]. The inelastic deformation of underfill FP4526 accumulated with temperature cycling is shown in Figure 26. The picture shows the fact that most of underfill inelastic deformation is generated during the first heating stage. Test results[55] showed the maximum strain of underfill FP4526 at 100°C is only about 2%. The deformation at the end of heating stage reaches 1.5% according to Figure 26. Therefore, the underfill at corner A could be broken at the initial thermal loading. Nonlinear Finite Element analysis[9] also showed that the fatigue life of Flip Chips with the underfill was reduced seriously when maximum extreme temperature exceeds above 100°C due to significant material softening. The conclusion is that the glass transition temperature T_g of underfill encapsulants is critical for the fatigue life of Flip Chip packages under the accelerated testing temperatures near or above the T_g since the thermal-mechanical properties of underfills are degraded seriously around T_g. Therefore, over-accelerated testing temperature is not necessary, which can result in unrealistic requirement for underfill material selection.

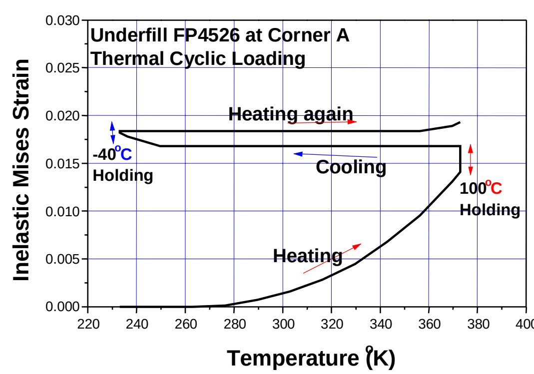

Figure 26. Accumulation of inelastic mises strain of underfill.

7. Conclusions

The life prediction methodology of solder joints under thermal cyclic loading has been summarized and critically reviewed in this paper. Energy-based approach could mislead the life prediction of solder joints under some accelerated conditions such as different ramping rates. Energy-based approach might not be suitable for life prediction of accelerated testing conditions, as shown in this paper and literature[27,29]. Strain-based approach is strongly recommended to combine with unified constitutive modeling for the reliability assessment of solder joints. The constitutive modeling plays an important role in the life prediction in terms of the correct calculation of inelastic strain ranges, inelastic strain energy density of hysteresis loop, and creep-plasticity interaction, under various accelerated test conditions. The separated constitutive modeling of rate-independent plasticity and creep should be used cautiously, in particular, considering the inconsistency and difficulty for the calibration of model parameters and the Finite Element analysis of solder joints subjected to thermal cyclic loading. Proposed bound concept of life prediction and the upper bound of accelerated testing factors obtained in this paper are very meaningful for industry practice. However, further investigation is definitely needed. Finally, the investigations of underfill strengthening mechanisms and life prediction of Flip Chip packages give valuable insights for advanced package design and reliability assessment.

Acknowledgment

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