CHAPTER 5
THERMOMECHANICAL FATIGUE IN SOLDER MATERIALS

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Introduction

Thermomechanical fatigue is the deformation condition that arises when structural material encounters temperature fluctuations while in service. The fluctuations result in induced cyclical strains. The combination of strain and temperature under low cycle fatigue conditions can result in the eventual failure of the structural member. The thermomechanical fatigue material response for pressure vessel steels has been the most extensively studied and documented, and is discussed in detail in Chapter 7. The material response of structural steels under conditions of thermomechanical fatigue has been characterized to the point where fatigue life predictive methodologies have been established against an extensive database. This state of understanding does not yet exist for solder alloys used as joints in electronic packages. These joints can also undergo thermomechanical fatigue.

The solder joints in electronic packages may not only be electrical interconnections, but may also function as mechanical bonds. The solder joints often constrain materials of differing thermal expansion that, when thermal fluctuations are encountered, impose cyclic strain throughout the joints. The thermal fluctuations can be caused by either changes in the external environmental temperature or internal heat dissipation by devices in the electronic package. The temperature fluctuations can be large (for example, temperature fluctuations for electronic components used in avionics) or small (for computers in a climate-controlled environment). Even small temperature fluctuations can have a large effect, depending upon the size of the joint and the difference in the thermal expansion of the joined materials.

Because electrical or mechanical catastrophic failure of solder joints is possible, a great deal of work has recently been performed to develop a better understanding of the metallurgical response of solder joints under conditions of thermomechanical fatigue. The research to date has been performed to satisfy three temporal needs:

- **Immediate: Engineering Predictions of Solder Joint Lifetimes.** This information is needed so that solder joints used in electronic packages can be designed optimally for conditions of thermomechanical fatigue. This work is based on engineering results, not fundamental understanding.

- **Longer Term: Solder Joint Lifetime Prediction Based on Fundamental Understanding.** These results need to be more accurate for lifetime prediction and consequent design purposes. However, much more fundamental metallurgical information is needed before this type of predictive modeling can be performed.

- **Long-Term: Alloy Development of Solders for Improved Thermomechanical Fatigue Behavior.** Based upon the fundamental metallurgical knowledge and understanding developed for solders
under conditions of thermomechanical fatigue, new solder alloys can be developed that have improved lifetimes over solders currently in use. Chapter 6 gives an overview of the alloy development process and additional information needed for solder alloy development.

This chapter discusses what is currently known about the thermomechanical fatigue of solders. The chapter presents metallurgical observations and the consequent current state of understanding. The goal is to delineate what is known, what is not well understood, and what further work is needed to develop the framework of fundamental metallurgical behavior of solder joints in thermomechanical fatigue so that the previously mentioned three needs can be satisfied.

Chapter Organization

This chapter is divided into four areas that summarize how research is being performed and what results are available for solders in conditions of thermomechanical fatigue:

- **Thermomechanical Fatigue Testing Methodologies.** This section discusses what solder fatigue testing methods are available and have been used, as well as the advantages and disadvantages of each. Methods are presented of imposing strain and temperature on the solder, as well as how to determine when a failure has occurred.

- **Metallurgical and Mechanical Observations.** This section discusses the metallurgical and mechanical properties of solders and addresses the following questions:
  - How does the microstructure evolve during thermomechanical fatigue?
  - What mechanical properties are known and how do they change during thermomechanical fatigue?
  - What effect does the environment have on thermomechanical fatigue?
  - What is the mechanism by which solder joints fail during thermomechanical fatigue?

- **Discussion of the Current Observations of Thermomechanical Fatigue of Solders.** This section is the highlight of the chapter. The critique presented is strongly influenced by discussions at the Solder Mechanics Workshop* and by observations from the existing literature. The intent is to answer the following questions:
  - What areas are well understood?
  - What areas remain controversial?
  - What are the best methods for testing and analysis?
  - Can solder microstructural evolution and mechanical properties be predicted given specific conditions of thermomechanical fatigue?

* The Solder Mechanics Workshop was held June 6–8, 1990 in Santa Fe, New Mexico, during which two sessions focused on the fatigue behavior of solders.
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- What microstructures are unstable and under what circumstances can they become stable?
- To what extent can thermomechanical fatigue and isothermal fatigue behavior be reconciled, and how?

• Summary of Future Work Needed. This section summarizes what testing programs and results are needed to more fully understand the thermomechanical fatigue of solder in order to support the goal of modeling and preventing failures.

Thermomechanical Fatigue Testing Methodologies

A number of diverse methodologies exist for testing solder joints under conditions of thermomechanical fatigue. The methodologies are categorized into four types for this review:

• Thermal cycling of actual components
• Thermal cycling of simplified test specimens
• Thermomechanical fatigue of bulk solder joints
• Thermomechanical fatigue of solder joints.

The following paragraphs describe these methodologies. Specific examples of the work that has been published in the literature are cited. Each summary includes a discussion of how the temperature is cycled, how the strain is imposed, how the failure is defined and measured, and what the advantages and disadvantages are of each method. Metallurgical structure results from these tests are presented later in the chapter.

Thermal Cycling of Actual Components

This type of testing represents the largest body of work performed to examine the thermomechanical fatigue of solders. In this methodology, electronic components are soldered to boards using normal production methods. The whole assembly is then thermally cycled. The strain is imposed on the solder joints by the difference in thermal expansion between the component and the substrate. The great advantage of this testing method is that an actual product is tested and a fatigue life for that given geometric configuration can be derived. The following paragraphs describe how this testing is performed.

Imposition of Strain and Temperature

A change in temperature simultaneously imposes strain on the solder joints of electronic assemblies. The time-temperature profile used on the test assemblies is usually one of the three patterns used as a basis for all the types of thermomechanical fatigue testing discussed in this chapter. The profiles are sine wave, sawtooth, and sawtooth with hold times. Figure 1 shows a schematic illustration of these profiles. There are also three ways to apply temperature to the test items: thermal shock, thermal cycling, and power cycling. The mechanical strain rate resulting from thermal shock testing is generally much faster than for the other two methods. Note here that there is a difference between mechanical strain rate and thermal cycle frequency. These two terms are often confused in the literature as having the same meaning; they do not. Thermal
cycle frequency is the total time to run a full thermal cycle, including any hold times. Mechanical strain rate is the rate at which strain is imposed on the solder joints in going from one temperature extreme to another. The strain rate is metallurgically more meaningful than cycle frequency because it deals with the rate of deformation induced and (as is discussed later) has a very strong effect on the thermomechanical fatigue properties.

As a rule, all tests are performed at an accelerated rate (tens to hundreds of cycles per day rather than the actual use conditions of 1 or 2 cycles per day). Tests are accelerated to complete the test in a reasonable length of time (for example, testing the thermomechanical fatigue response of the 20 yr. lifetime of a soldered component in a month). Englemaier [1] emphasizes that care must be taken when performing accelerated tests to ensure that the results are representative of real service and not an artifact of the test itself. The problems Englemaier discusses involve deformation rate and board warpage. If the acceleration rate is
too high, the stress imposed upon the joints becomes larger than it would under normal operating conditions because there may be no time to adequately relax the stress. He emphasizes that sufficient hold times at the temperature extremes are needed to relax the stress to simulate actual conditions. Furthermore, over acceleration could cause the board and components to become warped [2], resulting in a testing geometry that the joints would not be in under actual service conditions.

**Thermal Shock**

The temperature is cycled in the thermal shock mode by alternately exposing the soldered assemblies to hot and cold liquid baths with a hold time at each temperature extreme to reach thermal equilibrium. The thermal profile consists of temperature ramps with hold times at the extremes. Due to the rapid transfer of heat between the liquid baths and the test assemblies, the deformation rate is very rapid and this could damage some electronic components. However, this is an easy test to perform and accelerated results are achievable. Karjalainen et al. [3] and Kubik and Li [4] used the thermal shock methods on leadless ceramic chip carriers (LCCs) mounted on printed wiring boards (PWBs) for the temperature ranges from $-40^\circ$ to $125^\circ$C [3] and $-55^\circ$ to $125^\circ$C [4] for 15 min to 2 h hold times. The total strain and strain rates were not discussed.

**Thermal Cycling**

In this method, the temperature is cycled by introducing hot or cold air (or an inert gas such as nitrogen) onto the soldered samples. Heat is transferred less rapidly with a gas compared with a liquid, so the deformation rates are slower in thermal cycling than in thermal shock. Consequently, this technique is used more often than thermal shock because of the lessened possibility of damage to the components. All three thermal profiles have been used in thermal cycling tests: sine wave [5–7] sawtooth [8], and sawtooth with hold times [9–18]. For the most part, the thermal cycling experiments follow the temperature range cited in MIL-STD-883B: $-55$ to $125^\circ$C. Ramp times varied from 3 min [9] to 5 h [10] and hold times from 1.5 min [11] to 2 h [10].

**Power Cycling**

In power cycling, the temperature is cycled by turning the electronic devices on and off. The high-temperature portion of the cycle is generated by dissipating heat out of the package and into the solder joints when the device is turned on, typically at $150^\circ$C. The low-temperature portion of the cycle is typically room temperature or the temperature that the device is at when it is turned off. Englemaier [19] emphasizes that power cycling is very important and can be the primary source of thermomechanical fatigue, especially for consumer electronics. The effect of power cycling by itself has been studied [20, 21] along with the effect of externally imposed thermal cycles and power cycles combined together. The addition of power cycling has been noted to decrease the thermomechanical fatigue lifetimes of solder joints [22, 23].

**Failure Determination**

A number of techniques have been described in the literature for determining when the solder joints fail on actual components that are thermally cycled. The
definitions of failure are diverse and seem somewhat arbitrary. This makes comparisons between test results difficult because failures are often test dependent.

The most common method of failure determination is visual inspection [3–7, 12, 14–18, 24, 25]. The solder joints are inspected for cracks under a binocular microscope at the relatively small magnification of ∼40X [4–7, 13–16, 18]. Metallographic sectioning of the joints has also been used as a means to determine failure by polishing the joints after thermomechanical fatigue and examining for cracks [3, 12, 17]. An example of the definition of failure with the visual inspection technique is the point at which a visible crack length equals the lead width.

An interesting technique that is a variation of the visual inspection technique has been proposed by Marshall [13], where the visual appearance and number of cracks present in a joint is assigned a "fatigue level" on a scale of 0 to 9. The surface appearance has been correlated by metallographic sectioning. The fatigue level at which a joint fails is up to the user, but it is claimed that consistent comparisons can be made with the trained eye. A definition of the various values is shown in Table 1.

Table 1. Thermomechanical fatigue level.

<table>
<thead>
<tr>
<th>Grade</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No visible signs of strain</td>
</tr>
<tr>
<td>1</td>
<td>Light surface crazing</td>
</tr>
<tr>
<td>2</td>
<td>Surface crazed</td>
</tr>
<tr>
<td>3</td>
<td>Surface heavily crazed</td>
</tr>
<tr>
<td>4</td>
<td>Surface heavily crazed; flakes or small pits</td>
</tr>
<tr>
<td>5</td>
<td>Pitted surface</td>
</tr>
<tr>
<td>6</td>
<td>Surface cracks, less that 20° around the joint</td>
</tr>
<tr>
<td>7</td>
<td>Surface cracks, less than 360° around the joint</td>
</tr>
<tr>
<td>8</td>
<td>Surface crack 360° around the joint</td>
</tr>
<tr>
<td>9</td>
<td>Large crack 360° around the joint</td>
</tr>
</tbody>
</table>

Torque testing after thermal cycling has also been used as a metric to determine when a joint has failed [7, 11]. A socket is placed over the soldered component and a torque wrench is used to remove the component. A decrease in the torque needed to remove the component has been used as a baseline for failures.

Electrical and thermal measurements are probably the most accurate method to determine the number of cycles to failure of a solder joint in thermomechanical fatigue. This technique tests actual components because it is easy to measure the thermal or electrical impedance on electronic devices. Bangs and Beal [9] monitored activated light-emitting diode (LED) components soldered to boards that were thermally cycled. Upon solder joint failure, the LEDs turned off. Montante and Kling [23] monitored the current to the devices through the solder joints during thermal and power cycling using a four-point probe. This technique, however, could only determine a complete electrical open circuit.
A number of investigators used electrical resistance and thermal impedance to determine whether a crack was present [8, 20, 21]. Thermal impedance was found to correlate more accurately to the presence of cracks than did resistance measurements [20, 21]. Burgess et al. [8] also used ultrasonic measurements of thermally cycled Si diodes soldered to Cu and found that the presence of cracks caused a dramatic increase in the thermal impedance. Kang et al. [21] found that the thermal impedance was very sensitive to the early formation of cracks, while electrical resistance did not degrade until after the joints were completely broken.

**Advantages and Disadvantages to Thermal Cycling of Actual Components**

The great advantage of this technique is that the thermal fatigue lifetime data can be directly applied to a given system. Because the components on the boards are working electronic devices, it is possible to monitor the electrical and thermal continuity for a meaningful number of cycles to failure. The information is system specific, however, and caution must be used when extrapolating from one system to another.

A difficulty with this testing method is that the strain and stress states in the actual solder joints are quite complex. Hall [10, 26, 27] has characterized the strain in actual solder joints for leadless ceramic carriers (LCCs) soldered to printed-wiring boards (PWBs) using holographic techniques [26, 27] and strain gages [10, 27]. Hall could make force displacement plots based on these measurements (Figure 2) and found that the LCC and PWB expanded freely—all the strain was taken up by the solder joints. Hall also found that three modes of displacement are possible in solder joints: in-plane displacement, out-of-plane rotation, and out-of-plane displacement. These modes are plotted in Figure 3. Lau, Rice, and Avery [28] used two- and three-dimensional finite element models on surface-mounted joints and found that even in a single joint, for any given displacement, there was a complex state of tension, compression, and shear. The finite element method models also showed that even small changes in joint to joint geometry had a large effect on the strain and stress states.

The thermal cycling of actual components does not permit the meaningful measurement of solder joint mechanical properties. Even if mechanical properties were measured, the complex strain nature of the joints would make the analysis very difficult. Extracting fundamental metallurgical information from this type of testing is also very complicated.

**THERMAL CYCLING OF SIMPLIFIED TEST SPECIMENS**

This method avoids the problem of complex strain distributions in actual component assemblies by simplifying the state of strain in the solder joints. Prototype solder joints are thermomechanically fatigued by using the solder to join materials of different thermal expansion, and then cycling the sample between two temperature extremes. Nominally, the strain imposed is either in simple shear or in a tension–compression orientation, as defined by sample geometry. The following paragraphs discuss examples of this kind of testing.

One method to impose strain is to form a solder joint between metals of differing thermal expansion. The metals are usually plated with a Ni or Cu layer to
improve solderability. Bourcier and Stephens [29] used plated stainless steel/solder/Al and kovar/solder/stainless steel assemblies to impose 6% to 12% shear strain on the solder joints during thermal cycling. Figure 4 shows this sample geometry. Other studies [30–36] used samples of Cu/solder/Al(Cu plated)/solder/Cu to impose shear strains of up to 20% under thermal shock conditions (Figure 5). Frear [37] also used a similar set of materials fixtured to impose tensile–compressive strain on solder joints using thermal shock.

Munford [25] and Jarboe [38] utilized the difference in thermal expansion between metals and polymer encapsulants to impose 2% to 4% shear strain on solder joints during thermal cycling. Figure 6 shows the sample geometry. A Cu pin is soldered into a Cu-plated PWB and this assembly is then foamed with an encapsulant. The foam underneath the pin bonds to the metals, and expands and contracts more than the pin, causing the pin to be displaced relative to the solder. Visual inspection (at 40X) for cracks as well as subsequent cross-sectional metallography was used to determine failure.

![Figure 2](image-url)  
**Figure 2** Experimental force versus displacement plot from Hall's [10] experimental measurements on leadless chip carriers soldered to printed wiring boards that were thermally cycled. Plot courtesy of P. M. Hall and reprinted by permission of ©1984–IEEE.
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\[ \theta = \frac{(a - a_0)}{h} \]

\[ \Delta \theta = \frac{(a / h) \Delta (\varepsilon_2 - \varepsilon_1)}{h} \]

\[ \Phi = \frac{a}{R} \]

\[ \Delta \Phi = (a / R) \Delta (\varepsilon_3 - \varepsilon_2) \]

\[ \Delta \Psi = \Phi / h \]

Figure 3 The three modes of displacement that can be imposed upon solder joints under conditions of thermomechanical fatigue.

Figure 4 Simplified test specimen used by Bourcier and Stephens [29]. The shear strain is imposed to the solder joint by a combination of the thermal cycles and the difference in thermal expansivity between the two constraining materials.
Figure 5  Simplified test specimen used by Freer et al. [30–36] to imposed shear strain on the solder joints. The shear strain is a maximum at the ends of the specimen and decays linearly to zero in the center. The Al center piece was plated with Ni then Cu for solderability.

Figure 6  Sample used by Jarboe [38] to impose shear strain on solder joints. The "thumbtack" pin is soldered into a printed-wiring board. The encapsulant is cured over the pin and the difference in thermal expansivity between the pin and the encapsulant imposes a shear strain on the solder joint.

Advantages and Disadvantages

The advantage of this type of testing is that the externally imposed strain state on the solder joints is greatly simplified; therefore, the solder microstructural
evolution and failure characterization of solder joints in actual electronic devices can be easily studied. However, there are no means by which mechanical properties can be determined. Furthermore, the determination of the number of cycles to failure is not accurate, samples must be removed from the test and inspected or sectioned to find evidence of cracking. Electrical or thermal measurements are impractical because the entire test specimen can conduct heat and current. Failures cannot be determined as they happen, only after the fact.

THERMOMECHANICAL FATIGUE OF BULK SOLDER SPECIMENS

This is the principle technique used for the thermomechanical fatigue testing of structural materials, and is discussed in depth in Chapter 7. The specimens are made of bulk materials and strain is imposed externally by a loadframe. Elevated temperatures are normally applied by resistance heating coils, and forced chilled air cools the sample for the low-temperature extreme.

This type of testing has been applied to bulk solders by Lawson [39–40]. The sample was a flat dog bone design. Heating was generated by radio frequency heating coils in the grips, the sample was cooled by forcing refrigerated freon through machined chambers in the grips holding the specimen. Temperature cycles ranged from 25°C to 80°C and 15°C to 60°C. A tension–tension strain of 0.5% to 3% and was imposed by a loadframe using either a sawtooth or temperature ramps with hold times cycle.

The most common method of failure detection for bulk samples in isothermal fatigue is a percentage drop in initial load. However, the accuracy of this method is compromised because it depends on an arbitrarily selected load drop. Furthermore, a decreasing load could correspond not only to crack formation but also microstructural changes and strain softening. Lawson found that the use of just a load drop alone was an insufficient descriptor of failure. Therefore, Lawson defined failures by an internally consistent combination of visual inspection (when cracks equal to the grain size of the solder could be found on the surface of the specimen) and a percentage drop in load.

Advantages and Disadvantages

The advantages of thermomechanical fatigue testing of bulk solder specimens are that a simplified tension–tension strain state over any variety of strains can be achieved and one can collect mechanical data while testing. Furthermore, this technique is similar to that used for isothermal fatigue (Chapter 4), so a correlation between thermal and isothermal fatigue results can be made.

One drawback to this test method is that the specimen is fairly massive, and no correlations have been made between a large bulk sample and a small solder joint. Another difficulty is that samples can only be tested easily in tension–tension; tests performed under shear modes of deformation have not yet been published.

THERMOMECHANICAL FATIGUE OF SOLDER JOINTS

This method of performing thermomechanical fatigue attempts to combine aspects of a simplified strain state with mechanical data collection on smaller
scale solder joints. Frear proposed the method and it is discussed in depth elsewhere [42-44]. A servo-hydraulic loadframe under strain control imposes strain. The specimen is designed so that electrically isolated solder joints can undergo any desired magnitude of shear deformation. Figure 7 shows the specimen design. The temperature is cycled by resistively heating air that is blown over the sample or cooled by liquid nitrogen vapor injected over the sample. This method can achieve cycling from –55°C to 150°C. The temperature and strain are controlled digitally, and mechanical data is stored on a computer.

Failures for the solder joints are determined by using a continuity monitoring technique. Failures are determined by a persistent spike in resistance over a short period of time (~0.2 \( \mu s \)). This technique for defining a failure correlates well with the definition of a joint failure in an electronic package. The advantage of continuity monitoring over resistance measurements is that the temperature dependence is eliminated. In shear deformation, physical contact between two surfaces can be maintained even with a crack present. However, asperities in the fracture surface will cause the crack to momentarily open as one surface is dragged across another. The momentary crack opening results in short transient spikes that are not detectable in a resistance measurement but are discernable using continuous continuity monitoring.

Englemaier [1] states that continuity monitoring is the best method for determining failures. Based on our experience [42-44], we agree. As described previously, visual inspection for cracks is not definitive and the process is time consuming. Resistance measurements, as discussed previously, are also inappropriate.
Advantages and Disadvantages

The advantage to performing thermomechanical fatigue on solder joints is that the strains are simple and in shear, the most prevalent loading condition of solder joints in electronic packages. Mechanical response parameters are easily measured with the loadframe and a definitive, accurate failure monitoring technique is utilized. The major drawback to this testing technique is that the test is difficult to perform because it is time consuming and needs special fixturing on the loadframe.

Metallurgical and Mechanical Observations

A great deal of metallurgical information exists in the literature describing the response of solder alloys to conditions of thermomechanical fatigue under the variety of testing techniques described previously. Here we present and discuss microstructural, mechanical, and metallurgical observations as a function of solder alloy composition. The details covered are microstructural observations, mechanical observations, proposed failure mechanisms (metallurgical mechanisms preceding failure and crack propagation behavior), and environmental effects (if any have been noted). The alloys covered are

- Near eutectic Sn–Pb
- High–Pb content Sn–Pb solders
- Other solder alloys (Bi containing solders, Sn–Ag solder, and In-bearing solders)

This section concludes with a relative ranking of the lifetime of the solders based on results published in the literature.

NEAR EUTECTIC Sn–Pb SOLDERS

The most commonly used solder in the electronics industry is near eutectic Sn–Pb. The compositions typically used are 60Sn–40Pb and 63Sn–37Pb. These solders have a relatively low melting temperature (183°C) with excellent wetting properties. Due to their widespread use, the near eutectic Sn–Pb solders have also been the most extensively studied solder alloys under conditions of thermomechanical fatigue.

The as-solidified microstructure of near eutectic Sn–Pb solders is a two-phase structure of either lamella or globules of Sn and Pb–rich phases. Off eutectic solders tend to have more Pb (60Sn–40Pb), so these solders will form some proeutectic Pb–rich dendrites. The microstructure is further divided into regions of similarly oriented lamella called eutectic cells or colonies. Figure 8 shows an optical micrograph typical of the near eutectic Sn–Pb solders.

The as-solidified structure of near eutectic Sn–Pb solders is not stable with respect to aging conditions or mechanical deformation. Upon isothermal aging, the phases in the near eutectic microstructure will coarsen. Mechanically deforming and heating near eutectic Sn–Pb solders results in recrystallization and the formation of equiaxed Sn and Pb–rich phases. It has been shown that this microstructure behaves in a superplastic manner. Schmitt-Thomas and Wege [14] found 60Sn–40Pb to have the least microstructural stability of all the
Sn–Pb solders that they investigated. They found that extensive coarsening and surface roughening occurred under conditions of stress relaxation and creep. Therefore, it is expected that conditions of thermomechanical fatigue, which involve both mechanical deformation and time at temperature, could have a great effect on the microstructure and properties of near eutectic Sn–Pb solder joints.

Wild [16] was the first to examine and metallographically document his observations of 60Sn–40Pb solder joints after thermal cycling. The solder joints consisted of pins soldered into plated through holes that were thermally cycled between -55°C and 125°C. Wild found that after thermal cycling the surface of the solder joints became "frosty," and he postulated that this surface relief was due to slip displacements in the solder. He found evidence that the microstructure of the solder coarsened on the interior of the joint parallel to the direction of imposed shear strain (Figure 9). He found this coarsening only under low-cycle conditions. In high-cycle fatigue, the joints simply fractured with no microstructural evolution. Wild also noted that the Pb–rich phases in the joint aligned after thermal cycling, and he postulated that failure must occur through the Pb–rich phase because this is the weaker of the two phases in the solder. Finally, he stated that the effect of stress relaxation during thermal cycling would be expected to have a great effect on joint lifetime and as cycle frequency decreases, the fatigue life of the joint should also decrease, but no experimental evidence was given.
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Figure 9 Optical micrographs of cross sections of plated pin-through-hole solder joints that underwent thermomechanical fatigue. Note the heterogeneous coarsening present in the solder joints parallel to the direction imposed shear strain, and the presence of cracks through the heterogeneous coarsened bands. Photographs reprinted by permission of the Journal of Welding.

Wolverton [17] thermally cycled LCCs and leaded carriers. He observed that prior to failure, the solder joints had bands of coarsened two-phase material parallel to the direction of the imposed shear. Figure 10 shows these bands. The joints showed evidence of cracking in the area of high strain under the LCCs and propagated out into the fillet of the solder joints. Cracks were thought to go through the Pb-rich phase. The observation of failure through the Pb-rich phase for both Wolverton and Wild could be associated with the metallographic polishing that reveals both the cracks and Pb-rich phase to appear dark. Unfortunately, the micrographs are not definitive of the true location of crack initiation and propagation.

Bangs and Beal [9] observed similar heterogeneous coarsening of the solder on thermally cycled dual-in-line-packages (DIPs) on PWBs. The solder coarsened adjacent to the pin in the direction of imposed shear strain. Like Wild [16], Bangs and Beal proposed that fracture occurs due to slip in the solder with evidence of striations on the fracture surface of the solder joints. Similarly, Harada and Satoh [46] found striations on the fracture surface of controlled collapse 63Sn–37Pb solder joints that were thermally cycled. Harada and Satoh claim that the striations are actually evidence of the advancement of the propagating crack.
Solder Mechanics

Figure 10 Scanning electron microscope and optical micrographs of the solder joints in leadless chip carriers that underwent thermomechanical fatigue. Note that the presence of cracks on the surface of the joints indicates a crack that has been present for a number of cycles that had not yet propagated through the entire joint. The cracking follows the heterogeneous coarsened bands. Photographs courtesy of W. M. Wolverton and reprinted by permission of Wela Publications Ltd.

Heterogeneous Coarsening

The heterogeneous coarsening of near eutectic Sn–Pb solders described previously has been extensively studied. This is an important microstructural feature because the coarsened region is inherently weaker and is known to be the region through which cracks propagate to final solder failure in thermomechanical fatigue.

The heterogeneous coarsening of near eutectic Sn–Pb solders has been characterized under a variety of thermal conditions, ranging from thermal shock [4, 9, 30–32, 34–37] to slow thermal cycling [12–15, 17, 42–44]. It has been determined that the rate at which deformation is imposed has a great effect on the heterogeneous coarsened region.

In thermal shock, the deformation rate is rapid, on the order of $7 \times 10^{-3}/s$ or faster. The heterogeneous coarsened band that forms is parallel to the direction
of imposed shear strain and appears to be independent of any microstructural features. The band first appears as a thin region of coarsened Pb and Sn-rich phases. As the number of thermal cycles increases the band increases in width [42–44] until the entire joint is coarsened, or a crack forms in the joint. Figure 11 shows an example of a heterogeneous coarsened band that has formed under conditions of thermal shock.

Figure 11 Heterogeneous coarsened band that formed in a 60Sn–40Pb solder joint under conditions of thermal shock. Note how the coarsened band cuts through the joint and is not directly associated with microstructural features.

At slower deformation rates, that are present under conditions of thermal cycling (less than $1 \times 10^{-5}$/s), heterogeneous coarsening results in a different microstructure [12–15, 42–44]. The heterogeneous coarsened band, moving at a slower deformation rate, meanders through the joint but is most prevalent parallel to the direction of imposed shear strain. Figure 12 shows an example of the coarsening under conditions of thermal cycling. Lee and Stone [12, 15], Tribula et al. [35, 36], and Frear et al. [42–44] proposed that coarsening during thermal cycling occurs at cell boundaries. Evidence of surface relief on joints after thermal cycling corresponds to the location of cell boundaries (Figure 13).
Figure 12  Heterogeneous coarsening that forms in a 60Sn–40Pb solder joint under the slower deformation conditions associated with thermal cycling. Note that the coarsening occurs at cell boundaries that are more or less parallel to the direction of imposed shear strain.

A mechanism of coarsening at cell boundaries has been proposed [32, 34–37]. After solidification, cell boundaries are slightly more coarsened than the rest of the lamellar solder and are therefore the “weak link” in the microstructure. During the low-temperature portion of the thermal cycle, deformation concentrates at the cell boundaries and the cells slide or rotate relative to one another [12, 15]. At the high-temperature portion of the cycle, this deformation is annealed out either by recrystallization at the cell boundaries [30–32, 34–37, 42–44] or, as McKay has proposed [47], via a stress-assisted diffusional mechanism where diffusion of material occurs into the regions of highest stress in the joint resulting in subsequent coarsening. By either mechanism, a heterogeneous coarsened region develops that has the same appearance as for a near eutectic Sn–Pb alloy that has been mechanically worked then heated [45, 47]. This similarity is shown in the worked and heated superplastic microstructure of bulk 60Sn–40Pb in Figure 14 and in the heterogeneous coarsened band in Figures 11 and 12. The coarsened cell boundary is still weaker than the rest of the microstructure so that any further deformation and subsequent recrystallization will concentrate there. Eventually, cracks form in the coarsened band, either through the Sn–rich phase [42–44], through the Pb–rich phase [16, 17] or at the Sn–Pb phase boundaries [9, 12, 15]. All three failure paths have been observed.
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Figure 13  Scanning electron and optical micrographs that show the cracking in a near eutectic Sn–Pb solder joint is associated with the eutectic cell boundaries. B) and C) are of the same area before and after polishing. Photos courtesy of D. S. Stone [12] and reprinted by permission of ©1990-IEEE.

A possible reason for the difference in appearance of the heterogeneous coarsened regions between thermal cycling and thermal shock is that in thermal shock, the strain rate is so great that the cell boundaries are unable to slide relative to one another, so coarsening occurs independent of the cell boundaries. It is still unclear why, but if the cells do not rotate, the coarsening develops in a band parallel to the direction of imposed shear strain and independent of any microstructural features of the solder joint.

Note that the process of heterogeneous coarsening at cell boundaries has also been observed in some isothermal fatigue tests at slow strain rates [35, 36, 43] and isothermal creep tests [35, 36]. However, in the isothermal tests, the heterogeneous coarsened band is much thinner, as shown in Figure 15. Furthermore, the strain rate influence on the different types of heterogeneous coarsened bands is also clear in the creep tests [35], but this situation occurs at much slower rates. At deformation rates slower than $1 \times 10^{-8}$/s, the coarsening follows cell boundaries; however, at rates faster than $1 \times 10^{-6}$/s, the heterogeneous coarsened band cuts across the cells parallel to the imposed shear strain.
Some work [4, 6] has shown that as cycle frequency increased, the thermomechanical fatigue life increased and the accumulated damage decreased [4, 6]. The explanation for this phenomenon was that hold times were not accounted for, and the additional stress due to stress relaxation could not occur. This resulted in less damage accumulation and therefore longer lifetimes. Other work [43] clearly shows that as deformation rate increases, the accumulation of damage in the solder joint also increases and the consequent thermomechanical fatigue lifetime decreases. A difference between these two observations is that in the frequency tests the deformation rate is not explicit and it is possible to vary the frequency while keeping the deformation rate constant. In fact, for most thermal cycle tests, the deformation rate is determined by how fast heat is exchanged at the two temperature extremes, and this rate is usually a constant. It is clear that the deformation rate is the determining factor in the microstructural response and thus the ultimate failure.

The effect of hold times at the temperature extremes in thermomechanical fatigue can also have an effect on damage accumulation in the solder, and the amount of accumulation is dependent upon the temperature extremes themselves. At the high-temperature portion of a thermal cycle (80°C and above), the stress will relax to zero in less than 1 min [42–44]. At a low-temperature extreme (−55°C), the stress will not relax to any significant degree over a period of days [42–44]. Therefore, if hold times at the elevated temperatures are extremely short, additional damage will accumulate and the life can be shortened. However, the hold time effect is secondary with respect to the effects of deformation rate.
It is not only the thermal expansion difference between components that causes problems in thermomechanical fatigue; the difference in expansion between the component and the solder itself is also involved [30]. The heterogeneous coarsening process is the same as for strain imposed by the difference in expansion between the components, but it takes a greater number of cycles [30]. This is an effect especially important for electronic packages with matched substrates.

Figure 15  Scanning electron micrographs of 60Sn–40Pb deformed in A) isothermal fatigue, and B) creep. Photographs courtesy of D. Tribula.

Effect of Strain Imposed

As is expected, an increase in the amount of shear strain imposed for a given joint thickness results in more rapid heterogeneous coarsening and more rapid failures. This is due to more damage imposed upon the solder joints. One design offshoot from this is that an increase in joint thickness should decrease the strain imposed and therefore increase the fatigue lifetime. However, recent work [37] has shown that, for near eutectic Sn–Pb solders, an increase in joint thickness does not have a large effect on the microstructural response. The study used 0.005-, 0.010-, and 0.020-in thick solder joints and found that they all cracked after approximately the same number of cycles under conditions of thermal shock of −55°C to 125°C and a total strain of 10% or more. This effect was attributed to the formation of a heterogeneous coarsened band in which all subsequent strain concentrated; this made the total thickness of the solder joint less relevant. However, under the slower deformation conditions of thermal cycling, an increase in strain results in a larger amount of heterogeneous coarsening and more rapid failure [43, 44]. Therefore, the total strain effect is also deformation rate dependent.
Effect of Tensile Strain in Thermomechanical Fatigue

As described previously, the strain state in solder joints is rarely simple. However, for test singularity, most studies are performed primarily in shear or on actual joints with a wide variety of strain orientations. One study [37] did look at the effect of tension–compression of 60Sn–40Pb under conditions of thermal shock. A dichotomy of results was found. Some joints failed through the interfacial intermetallics after a short number of cycles. The rest lasted at least as long as joints tested in shear for the same amount of strain. The near eutectic Sn–Pb solder tested in tension–compression underwent some heterogeneous coarsening, but the coarsening occurred at cell boundaries throughout the joint.

Effect of Aging Prior the Thermomechanical Fatigue

To simulate real conditions, a number of studies have been performed to examine how joints will behave after time at temperature. Keller [11] found that after aging, thermally cycled 60Sn–40Pb joints tested in shear failed through the interfacial intermetallic layer. The intermetallic phases thickened when the joints were aged and subsequently fractured rather than deformed. Other studies by Frear et al. [37] and Morris et al. [34] concurred with Keller; if the solder joint is thin enough and the intermetallics take up enough joint cross section, the joints will fail through the interfacial intermetallics even in shear thermomechanical fatigue. Figure 16 shows an example of this kind of failure. However, on thicker joints, interfacial intermetallics play no part in failure behavior. Karjalainen et al. [3] studied near eutectic Sn–Pb solder joints processed using a number of techniques (wave soldering, vapor phase reflow, and belt-infrared soldering) and as a result of differing cooling rates, different initial solder joint microstructures were obtained. However, after subsequent isothermal aging, the joints failed in a similar manner after approximately the same number of thermal cycles. This observation was attributed to the solder microstructure rapidly aging to the same final, more or less stable, state. Karjalainen et al. also claim that aging sufficiently coarsens the interfacial intermetallics to cause failure through the interface. Wright and Wolverton [18] similarly found that an initially coarse or fine microstructure is irrelevant to the final failure time and mode. They also found that the interfacial intermetallics do not to coarsen sufficiently to result in failure.

![60Sn - 40Pb Thermal Cycle: -55°C ↔ 125°C](image)

Figure 16 Optical micrograph of a near eutectic Sn–Pb solder joint that failed, partially, through the interfacial intermetallics in the joint.
Final Crack Propagation

The heterogeneous coarsened band provides the path through which cracks propagate in near eutectic Sn–Pb solder joints. Some claim that the failure occurs through the Pb–rich phase [16–17]. Their hypothesis is that Pb is softer than Sn and is therefore more easily deformed. However, in these studies, the microstructure was characterized well after failure, and the mode of initial cracking could not be determined. Some failures were observed to be by interphase separation [9, 12, 15]. Other investigators find cracks initiating and propagating through the Sn–rich phase [30–32, 34–37, 42–44] with some cracks in the Pb–rich phase to connect to the adjacent Sn. Figure 17 shows an example of the cracking of Sn–rich grains in the heterogeneous coarsened band. These cracks are thought to initiate when the large Sn grains (which coarsen at the same time as the phases in the heterogeneous bands) can no longer slide and rotate to accommodate the strain resulting in intergranular separation.

![Image](image_url)

Figure 17  Optical micrographs showing cracks in the Sn–rich grains of a thermomechanically deformed heterogeneous coarsened region.

One hypothesis is that stress assisted diffusion forms voids in the eutectic microstructure [20] and the voids connect and coalesce for the final failure. This hypothesis correlates with work by Kang et al. [21] who found that joints with a large number of pre-existing voids failed more rapidly that void-free solder joints, because cracks propagate easily between the voids.

Mechanical Properties of Near Eutectic Solders in Thermomechanical Fatigue

The documentation of mechanical properties of near eutectic Sn–Pb solders in thermomechanical fatigue is scarce. This is because most thermomechanical fatigue tests were performed on actual components where the stress could not be measured; what follows is the limited information available.

Some work has been performed on predicting the mechanical response of solder joints. Hall [10] measured the force imposed upon solder joints using strain gages. Hall assumed purely elastic conditions and could only derive strain, not stress. Stone et al. [49] modeled a simplified lap shear solder joint using Hart’s equations [50] to relate strain rate to stress and temperature. Stone et al. found that their model followed Hall’s [10] experimental strain gage data. The Stone
model predicts the effect of stiffness, frequency, and grain size on the stress imposed upon a solder joint.

Some mechanical property data has been derived from the thermal cycling of actual components by using a torque test on surface-mounted components [3, 7, 11, 23]. Measurements were made by placing a torque wrench on a package and measuring the force needed to remove the package from the board. A clear relationship between a decrease in strength with increasing number of thermal cycles was observed. Unfortunately, the large number of joints on each surface mount package and the fact that these are post-thermomechanical fatigue measurements does not allow for the dynamic measurement of stress in each joint. These joints are the sum of a large number of lead strengths on each package. However, this is a valid method for gross comparisons of given packages under a variety of conditions.

Other in situ mechanical properties on solder joints have been gathered [42-44] using the thermomechanical fatigue of solder joints test methodology. The tests were performed over a temperature range of -55°C to 125°C and strain ranges for 5% to 20% in shear; Figure 18 shows the results. It was observed that extensive stress relaxation occurs at the elevated temperature hold time, and very little stress remains after 1 min at temperature. The low-temperature stress has little or no relaxation over a period of hours. A drop in load with increasing numbers of thermal cycles was found to be a complicated function of microstructural coarsening that results in weaker material and the formation of cracks that decrease the area supported by the load.

The effect of strain rate is as great on the mechanical properties as on the microstructural evolution that was discussed earlier. At fast deformation rates \((5.5 \times 10^{-4}/\text{s})\), work hardening occurs in the solder joints at both the low and high temperatures. However, at slow deformation rates \((1.4 \times 10^{-4}/\text{s})\), the imposed deformation anneals out at the high-temperature portion of cycle as fast as it can be imposed, while work hardening still occurs at the lower temperatures. The plots in Figure 18 show the strain rate effect. At both deformation rates, the heterogeneous coarsening still occurs at cell boundaries.

HIGH-Pb CONTENT Sn–Pb SOLDERS

These solder alloys are of compositions ranging from 90Pb–10Sn to 97.5Pb–2.5Sn, which melt at higher temperatures than eutectic Sn–Pb \((270\,\text{°C} \text{ and above})\). These higher melting point solder alloys are commonly used for step soldering operations in combination with eutectic Sn–Pb where the eutectic can be reflowed without melting the high–Pb solder. An example of where high–Pb solder is used in an electronic package is for flip chip solder bonding inside a ceramic package that is subsequently soldered onto a board. The high–Pb solder joints, in this example, undergo thermomechanical fatigue due to the thermal expansion mismatch between the silicon chip and the ceramic package.

The high–Pb solders have a microstructure that consists of a primary Pb–rich phase with Sn precipitates throughout. Chapter 1 discusses details of the microstructure and precipitation processes.
Chapter 5: Thermomechanical Fatigue in Solder Materials

High load

Number of cycles

Fast Deformation Rate

(5.5 \times 10^4 \text{ /Second})

Low load

Slow Deformation Rate

(1.4 \times 10^4 \text{ /Second})

Figure 18 Plots of load versus strain–temperature for conditions of thermomechanical fatigue for a slow and fast strain rate. A) and B) are typical cycles for each strain rate and C) and D) show the various load positions indicated in A) and B) as a function of number of cycles.

The isothermal fatigue properties of high-Pb solders have been studied in depth. Chapter 4 discusses the details of these properties. The thermomechanical fatigue properties of these solders are not as extensively studied as for eutectic solders. However, a significant amount of work has been performed and the following paragraphs summarized this work.

Howard, Sobeck, and Sanetra [22] thermally and power cycled LCCs, from 0°C to 100°C, joined to alumina with 90Pb–10Sn solder. They found the joints lasted several thousand cycles and this was attributed to the almost matched thermal expansion between the LCC and the substrate. However, the joints were not examined metallographically. Montante and Kling [23] thermally and power cycled ceramic chip carriers, also bonded to ceramic with 90Pb–10Sn with a larger temperature cycle of –65°C to 100°C. After thermal cycling, the joints were evaluated by torque testing. Montante and Kling observed that as the number of cycles and aging time increased, the joint strength decreased. This was thought to be due to cracking but, again, no direct observations were made.
The first metallurgical observations were made by Levine and Ordonez [24], who thermally cycled assemblies of silicon joined to alumina. The solder used was 95Pb–5Sn. They cut both the chip and substrate to within 125 μm of the solder joints so that microscopy could be performed without post–test metallographic polishing. Levine and Ordonez compared large- and small-volume solder joints. In the large-volume joints, the difference in thermal expansion between the solder (−25 x 10⁻⁶ in/in°C) and the silicon (4 x 10⁻⁶ in/in°C) caused lips to form near the joint interface due to surface diffusion with a consequent decrease in the cross section of the center of the joints. Cracks were observed in the lip regions. For the smaller volume joints the thermomechanical fatigue, damage accumulates in the form of cracks throughout the joint. Figure 19 shows an example of cracked small-volume joint. Three failure mechanisms were proposed by Levine and Ordonez for this high–Pb solder:

- Pb–rich grain sliding and resultant intergranular failure
- Cracks initiating at a hard particle (trapped inclusion) matrix interface
- Cracks initiating at grain boundaries where slip through the Pb terminates

![Figure 19](image-url)

Figure 19 Scanning electron microscope micrographs of high Pb content Sn–Pb solder joints joined between Si and a ceramic substrate. Note that the surface of the solder becomes deformed with increasing numbers of thermal ON–OFF cycles. A) 0 cycles, B) 600 cycles and C) 1500 cycles. Photos courtesy of J. Ordonez [24] and reprinted by permission of ©1981-IEEE.
In Figure 19, the failure mechanisms appear to be both grain boundary cracking and particle-matrix cracking.

Frear [32] thermally shocked simplified lap shear test specimens of a sandwich configuration (Figure 5). The samples consisted of Cu/95Pb–5Sn/Al (plated with Ni and Cu)/95Pb–5Sn/Cu structure with a maximum shear strain of 20% at the end of the sample. With increasing numbers of thermal cycles, the 95Pb–5Sn joints cracked intergranularly. Figure 20 is an optical micrograph showing intergranular failure of this solder. Frear compared the results for 95Pb–5Sn with 60Sn–40Pb under the same conditions and found the eutectic solder had a much longer thermomechanical fatigue lifetime than the high–Pb solder.

Figure 20  Optical micrographs of a 95Pb–5Sn solder joint after undergoing thermomechanical fatigue under thermal shock conditions. Note that the cracks form and propagate along Pb grain boundaries.

The most extensive study of the thermomechanical fatigue of high–Pb solders was performed by Lawson [39-41]. Lawson used bulk flat dog bone test specimens of 96.5Pb–3.5Sn. The temperature cycles ranged from 15°C to 60°C and 25°C to 80°C over a low strain range of 0.3% to 3% in a tension–tension orientation. The principle failure mode observed was cracking at the Pb grain boundaries early in the fatigue life (Figure 21). The cracks, at the finest level, appeared to be the result of grain boundary grooving. The deformation prior to failure exhibited two interesting phenomena. First, at 3% strains, heavy slip lines were observed, whereas fine slip was observed at lower strains. Second, recrystallization of the
Pb decreased the average grain size of the Pb grains to 68% of their initial value after thermomechanical fatigue. However, the change in grain size was found to have little or no effect on the thermomechanical fatigue behavior.

![Scanning electron microscope micrograph of a bulk solder specimen of 97Pb-3Sn after conditions of thermomechanical fatigue.](image)

**Figure 21** Scanning electron microscope micrograph of a bulk solder specimen of 97Pb-3Sn after conditions of thermomechanical fatigue (15°C to 60°C 0.6% strain). Note that the cracks form intergranularly at Pb grain boundaries. Photograph courtesy of L. R. Lawson.

Lawson [39–41] determined that mechanical properties during the thermomechanical fatigue tests. The initial drop in load was attributed to back stress in the sample. The longer term drop in load corresponded to Sn lamella coarsening that results in a softer material (Figure 22). A significant load drop was observed when the surface crack depth was equal to one-half the grain size. The introduction of hold times at the temperature extremes decreased the number of cycles to failure. Interestingly, cavitation due to creep processes was not observed in samples with hold times. Lawson also looked at the effect of frequency using a sawtooth cycle. (By changing the frequency Lawson also changed the deformation rate.) He found that as the frequency decreases, the fatigue life increases for 96.5Pb–3.5Sn were the same as were found for 60Sn–40Pb [42]. Frequency has the opposite effect in isothermal fatigue.
Chapter 5: Thermomechanical Fatigue in Solder Materials

Lawson also investigated the effect of the phase relationship between temperature and strain on 96.5Pb–3.5Sn solder. Again, the samples were in a tension-tension orientation. He observed that the damage was most severe when the extremes of temperature and strain occurred 90° apart. The damage decreased to a minimum when the temperature extreme occurred 270° out of phase with the strain. Finally, Lawson observed that environment has a strong effect on fatigue life in high-Pb content solders. Samples that were hermetically protected from air and water had greatly increased lifetimes; this indicates that cyclic stress corrosion cracking may have a strong influence on the thermomechanical fatigue behavior of high-Pb solders.

OTHER SELLERS

Near eutectic Sn–Pb and high-Pb content Sn–Pb solders are the most commonly studied alloys under the conditions of thermomechanical fatigue. However, there is some work on other alloys, such as ternary Sn–Pb–Ag, non-eutectic Sn–Pb, In–bearing (low melting temperature solders), Sn–Ag eutectic, and Bi solders. The following paragraphs discuss results for these alloys.

Sn–Pb–Ag Solders

Solders that contain Ag were originally developed for thick-film Ag conductors on ceramic substrates to minimize silver leaching into the Sn–Pb eutectic solders.
Recently, there have been some reports that 62Sn–36Pb–2Ag has an increased lifetime over near eutectic solder joints without Ag under conditions of thermomechanical fatigue [6, 33, 51]. However, the literature is not clear on whether the Ag additions have an effect on the lifetimes in fatigue or even the mechanism by which the improvement occurs. In some studies, the fatigue life of 62Sn–36Pb–2Ag was found to be better than 60Sn–40Pb by a factor of two [6, 33, 51]. Conversely, it has also been found that the fatigue life of 62Sn–36Pb–2Ag was the same as 60Sn–40Pb [3, 14, 23, 52].

Two mechanisms by which the addition of Ag acts to increase the fatigue life of near eutectic solder have been proposed. The first suggests that the Ag combines with Sn to form fine Ag3Sn precipitates that pin the solder grain boundaries, thereby stabilizing or refining the solder microstructure [6]. The other hypothesis suggests that the Ag, in the form of precipitates or solid solution, hardens the solder and that harder solders (for undocumented reasons) tend to have longer fatigue lives [33].

One study specifically investigated the effect of Ag on near eutectic solders in thermomechanical fatigue [44]. This study found that the solder was tied up into rather large Ag3Sn precipitates in the bulk of the solder joint. A comparison of the fatigue life of the 62Sn–36Pb–2Ag solder with 60Sn–40Pb showed no difference. The isothermal, and thermomechanical fatigue mechanical properties between the two alloys were also virtually identical. It was concluded that the presence of Ag has no beneficial effect under thermomechanical fatigue conditions, and could have a slightly deleterious effect if the strong, brittle Ag3Sn precipitates were oriented parallel to the direction of fatigue cracks and thereby act as a path of crack growth (Figure 23).

![62Sn-36Pb-2Ag Solder Joint](image)

Figure 23 Optical micrographs of a 62Sn–36Pb–2Ag solder joint after 115 cycles of −55°C to 125°C. Note that the fatigue cracks form and propagate independently of the Ag3Sn precipitates in the joint.
Off Eutectic Sn–Pb Solders

Off-eutectic (and not high-Pb content) solders have found limited use in the electronics industry, and consequently the thermomechanical fatigue behavior is not widely studied. However, Bangs and Beal [9] thermally cycled DIP leads soldered to PWBs with the off-eutectic solders 50Sn–50Pb, 60Pb–40Sn, and 70Sn–30Pb and compared these results with 60Sn–40Pb. The thermal cycle used was −65°C to 150°C. This study was performed to examine whether or not the eutectic solder was the optimal alloy for thermomechanical fatigue considerations. The 50Sn–50Pb solder had more proeutectic Pb dendrites present, but heterogeneous coarsening of the solder was still observed. The 60Pb–40Sn solder had even more proeutectic Pb, and the heterogeneous coarsening was extensive. Cracking occurred primarily through regions with the greatest amount of Pb-rich phase. The 70Sn–30Pb had extensive proeutectic Sn-rich phase with extensive heterogeneous coarsening and cracking. Cracks occurred through both the Sn-rich and the Pb-rich phases. However, the cracking was not as severe for the off-eutectic solders as was found for 60Sn–40Pb eutectic for the same number of cycles. From this work, Bangs and Beal concluded that, in comparing off-eutectic with eutectic Sn–Pb solders, the near eutectic solders had the greatest propensity for joint failure.

50Pb–50In

Pb–In solders are commonly used in applications where the Sn is deleterious to intermetallic growth. (Sn-bearing intermetallics tend to grow more rapidly than In-bearing intermetallics; Chapter 2 gives a more in-depth profile of this subject.) Bourcier and Stephens [29] used simplified shear test samples (Figure 4) to thermally cycle 50Pb–50In from −18°C to 100°C. After 500 cycles, no macroscopic cracking was observed but the surface of the joint did exhibit some surface deformation (Figure 24). A comparison between 50Pb–50In and 60Sn–40Pb with 40In–40Sn–20Pb showed 50Pb–50In to be better under conditions of thermomechanical fatigue than 60Sn–40Pb, but slightly worse that 40In–40Sn–20Pb over this temperature range. The improvement in thermomechanical fatigue life was attributed to the better creep properties of the 50Pb–50In over the 60Sn–40Pb. Marshall [33] thermally cycled 50Pb–50In using pins soldered into plated through holes from −30°C to 100°C. No coarsening was observed in the 50Pb–50In microstructure. Again, the surface of the solder joints showed extensive surface roughening but no cracking was observed.

40In–40Sn–20Pb

This is a low-temperature melting (121°C) solder that has found a great deal of use for the low-temperature portion of multiple stage soldering operations. The alloy has a two-phase structure of Sn and Pb with In in both phases. Bourcier and Stephens [29] found the 40In–40Sn–20Pb solder joint was extensively deformed on the surface after thermal cycling from −18°C to 100°C using simplified shear test samples. No cracking was observed. The initial microstructure of the solder consisted of a fine irregularly shaped phases. After 500 thermal cycles, the microstructure was observed to slightly coarsen and the phases became more spherical. Frear [42] performed thermomechanical fatigue on solder joints of 40In–40Sn–20Pb from −55°C to 85°C. The microstructure of the 40In–40Sn–20Pb was found to refine under these conditions. The failure of the
joints was due to surface cracking and subsequent crack propagation into the joints (Figure 25).

Figure 24 Scanning electron microscope micrograph of the surface of 50Pb–50In solder after thermomechanical fatigue of a simplified test specimen. Note the rough appearance of the solder surface. Photograph courtesy of J. J. Stephens and R. J. Bourcier.

Eutectic Sn–Ag Solder

This is a high-temperature solder (melting temperature of 221°C) that has greater strength than most soft solders. Marshall [13, 33] found that the 95Sn–5Ag alloy has a longer life under conditions of thermomechanical fatigue than solders with less strength. Jarboe [38] found 95Sn–5Ag to have the best thermomechanical fatigue properties of the 29 alloys he tested. The solder has a stable microstructure during thermomechanical fatigue, and the thermal cycling studies performed by Marshall et al. [13, 33] found the alloy to fail through the interfacial (substrate–solder) intermetallics.

Bi–Containing Solders

Bi–containing solders are the focus of renewed interest because of recent efforts to replace Pb in solders. Bi–containing solders also tend to have low melting temperatures.

Marshall [13] thermally cycled pins in plated-through-holes soldered with 43Sn–43Pb–14Bi solder and compared it to 60Sn–40Pb. The microstructure of 43Sn–43Pb–14Bi consists of Sn–rich and Pb/Bi–rich phases. Upon thermal cycling, this solder coarsens more extensively than 60Sn–40Pb but fails in a similar manner through the heterogeneously coarsened region. The thermomechanical fatigue
life was found to be slightly shorter than 60Sn–40Pb using the fatigue level measurements described previously.

Schmitt-Thomas and Wege [14] thermally cycled 57Sn–43Bi solder joined to surface mount devices (with 60Sn–40Pb plated leads) and pins in plated-through-hole components on PWBs from −40° to 100°C. The 57Sn–43Bi solder was observed to exhibit extensive surface deformation. Furthermore, pores formed on the interior of the joint after thermal cycling. The pores were attributed to the formation of a low-melting (96°C) ternary Sn–Pb–Bi phase. Failure was due to linking of cracks between pores. Despite these observations, however, Schmitt-Thomas and Wege claim that 57Sn–43Bi is microstructurally more stable than 60Sn–40Pb and has a longer thermomechanical fatigue life.

Figure 25 Optical micrographs of 40Sn–40In–20Pb solder joints under conditions of thermomechanical fatigue. A) The initial microstructure, B) After thermomechanical fatigue. Note the refinement of the microstructure that occurs in thermomechanical fatigue. C) After the solder joint has cracked.

Ranking of Solders

Many studies have been performed to apply a relative ranking on the fatigue life of a number of solder alloys. These studies, by their nature, are comparative. The results are invariably test method-dependent (this point is discussed in depth in the following section) and comparisons between studies would be dubious, at best. However, the ranking results are worthy of discussion. The studies are solely based on the thermomechanical fatigue life of the solders; wetting and other
criteria are ignored. The thermomechanical fatigue life used is that defined by the respective authors.

As discussed previously, Bangs and Beal [9] compared a variety of Sn–Pb solders under conditions of thermal cycling. The solders were of composition 63Sn–37Pb, 50Sn–50Pb, 60Pb–40Sn, and 70Sn–30Pb. All exhibited similar coarsening and failure behavior, but the 63Sn–37Pb solder had the shortest life with the greatest propensity for cracking. This was possibly due to greater microstructural instability for the near eutectic Sn–Pb solder compared to the off eutectic solders that have a great deal of proeutectic phase present.

Bourcier and Stephens [29] thermally cycled simplified test specimens using 50Pb–50In, 40In–40Sn–20Pb, and 63Sn–37Pb solders. These solders were studied for use in applications where extensive deformation was needed. The three solders had similar lifetimes in thermomechanical fatigue with the 40In–40Sn–20Pb slightly better, followed by 50Pb–50In, with 63Sn–37Pb having the shortest life of the three alloys tested.

Frear [42] compared 60Sn–40Pb with 40In–40Sn–20Pb using the thermomechanical fatigue of solder joints test method. The 40In–40Sn–20Pb had a longer fatigue life than 60Sn–40Pb. The improvement was attributed to the microstructural refinement that occurs with the 40In–40Sn–20Pb.

Thermal shock tests were used to compare 60Sn–40Pb with 95Pb–5Sn solder using large (20%) shear strains [32]. The 60Sn–40Pb was found to have almost an order of magnitude longer life than 95Pb–5Sn. The 95Pb–5Sn underwent rapid intergranular cracking, whereas the 60Sn–40Pb first heterogeneously coarsened then failed.

Marshall [33] developed a ranking for solders based on visual appearance after thermal cycling. Figure 26 shows a plot of cycles to failure for seven solders. The correlation Marshall found was that the harder the solder, the greater its yield strength; therefore, the longer the fatigue lifetime.

Montante and Kling [23] compared 62Sn–36Pb–2Ag, 10Sn–90Pb, and 80Au–20Sn by thermal cycling actual components then measuring the torque needed to remove the soldered components. The greater the torque, the higher the ranking. They found the 80Au–20Sn to have the greatest strength after thermal cycling, but its high melting temperature limits the number of useful applications. (A note of caution should be made regarding high-strength solders for applications in thermomechanical fatigue. The high-strength solders may have a long lifetime, but they do not deform easily and will transfer strain to the components that may themselves subsequently break.)

Jarboe [38] evaluated 29 solder alloys under conditions of thermomechanical fatigue. The solders tested had melting temperatures in the range 120° to 260°C. Tests were performed by thermal cycling the assemblies with strain imposed by the difference in thermal expansion between the metallized Kovar pins and the encapsulant foam (Figure 6) over the temperature range –54° to 75°C. Again, Jarboe found that the greater strength solders had the greatest resistance to
thermomechanical fatigue, with 95Sn–5Ag and 95Sn–5Sb being the longest lived solders tested. Figure 27 shows a ranking of the 29 solders tested.

![Figure 26 Plot of the fatigue level of a variety of solder alloys and a function of the number of thermal cycles. Plot courtesy of J. L. Marshall.](image)

Discussion of the Current Observation Thermomechanical Fatigue of Solders

Research on thermomechanical fatigue of solder is fairly recent. There are, as yet, no definitive testing standards (such as ASTM) for the thermomechanical fatigue testing of pressure vessel steels. Furthermore, the fundamental metallurgical mechanisms involved in the thermomechanical fatigue of solder joints are still being developed. In an effort to gain consensus on the best testing techniques and on what was solidly known about the metallurgy during thermomechanical fatigue, a group discussion was held during the Solder Mechanics Workshop. The following is a discussion of the consensus reached, including both the majority and minority positions. The focus of discussion was in three areas: testing methodology, microstructure and mechanical properties during thermomechanical fatigue, and whether interpretations of thermomechanical and isothermal fatigue can be reconciled.

TESTING METHODOLOGY

The best method of thermomechanical fatigue testing of solders and therefore the one having most potential for standardization did not get resolved. The feeling was that the methods were too immature. However, the conditions for a thermomechanical fatigue test to be acceptable were outlined. To fully understand the metallurgy, and mechanics during thermomechanical fatigue, the test must be fully instrumented to get relevant mechanical data and document the microstructures. The majority of the tests performed to date, such as thermal cycling of actual or simplified components, give a measure of
microstructural evolution and crack formation but no quantitative information on the mechanical mechanisms. Therefore, full instrumentation is needed to collect data such as strain, loads (stresses), and quantification of when the solder joint fails.

Figure 27  Plot of the number of cycles to failure for a variety of solder alloys as a function of alloy. Data from Jarboe [38].

A great deal of discussion focused on the fact that failure determination is important and should be standardized. A key question from the discussion was: How does one define failure in a solder joint? The majority agreed that the best method was electrical discontinuity measurements (event detection), because this failure definition was application oriented. For the most part, the primary function of solder joints is to carry electrical current, and the inability to carry current without interruption is a good engineering definition of failure. As discussed previously, the advantage of event detection over straight resistance (thermal or electrical) is that a resistance measurement cannot monitor momentary deviations in current that the event detection method is capable of measuring. However, it was also felt that in terms of modeling and determining actual metallurgical mechanisms, event detection may not be useful. By the time
a joint has failed electrically, the solder is very severely cracked and useful metallurgical information is no longer available. It was proposed that a drop in load, or some similar method, would be useful. Again, the application of load drop as a failure definition is difficult because of possible microstructural effects that may change the load without cracks being present.

There are also a number of researchers who believe that thermomechanical fatigue cracks initiate on the very first thermal cycle, while others believe microstructural evolution precedes any cracking. This dichotomy of ideas further complicates the use of load drop as a failure indicator. The discussion made it clear that no method of failure determination is acceptable in all circumstances. There are a number of definitions that can be used, but a comparison of results are failure determination dependent and therefore can be meaningless. Therefore, although some methods exist, it was felt standardization of failure determination and a correlation between methods is still too immature and more work is needed.

The use of realistic testing conditions was brought up and has been strongly advocated by Englemaier [1]. The desire is not to recklessly alter the test environment from the actual use conditions. For example, solder joints that will be used in a stable indoor computer environment should not be subjected to a MIL-STD-883B test of −55°C to 125°C because these are temperatures they would never encounter. Excessive temperature cycles are often imposed upon solder joints in an effort to further accelerate a thermomechanical fatigue test. Unfortunately, changing the test temperature can alter the mechanism of deformation that the solder joints would encounter in service. The final emphasis from this discussion was that variations in test conditions from actual use conditions must be considered very carefully.

The effect of the phase relationship between temperature and strain was discussed. This effect is important for systems that have Joule heating effects (due to power cycling) that can cause the temperature and resultant strain to be out of phase. An example where this is important is in the first level of electronic packaging, when a chip is soldered to a chip carrier. In use, the chip will dissipate heat and expand. The conduction of that heat to the substrate will not be immediate, so the strain is imposed before the temperature is reached. This phase effect was studied in depth by Lawson [40, 41] on high-Pb content solders. Lawson found, as was discussed previously, that in-phase cycling (temperature and strain are in phase) results in the smallest number of cycles to failure. These results could lessen the concern of the detriment of Joule heating. The question was raised that Lawson’s tests were performed in tension–tension and this may be different than a shear orientation, so the phase effect may be testing dependent. At this point, the answers are not known.

MICROSTRUCTURES AND MECHANISMS

The majority of the work on the microstructure of solders has been on the Sn–Pb eutectic alloy because this is the solder most commonly used in electronic assemblies. The majority of the discussion at the workshop also focussed on the Sn–Pb eutectic.

It was generally agreed that heterogeneous coarsening was the primary mechanism that precedes failure in the near eutectic Sn–Pb solders. (Other
work, discussed previously, also noted the same type of coarsening for solders well off the eutectic [91] The areas that are the least well understood but generate the most interest dealt with the nature of the heterogeneous coarsened band. Namely, was the heterogeneous coarsened region superplastic, or can a solder joint by itself exhibit superplasticity? The microstructure and morphology of the heterogeneous coarsened region has an appearance that is very similar to that found for superplastic Sn–Pb alloys [45]. Data from creep tests on solder joints was presented and discussed at the workshop [53–55] that showed that solder joints exhibit superplastic behavior insofar as the creep rate is concerned. The data was unclear as to whether the joints are initially superplastic because of a rapid cooling that causes a fine structure to form, or because of a rapid heterogeneous coarsening process.

One-half of the question is whether the solder joints are superplastic—the natural second half of the question is whether superplasticity is good or bad from a thermomechanical fatigue life perspective. Chapter 6 discusses this question. The topic of fatigue of superplastic materials has not been studied, and data is needed for answers. The question of superplasticity in solder joints pointed out a number of areas in need of deeper understanding. These are

- Is the heterogeneous coarsened band superplastic?
- What are the mechanisms of fatigue in superplastic materials?
- Can a solder joint be superplastic without heterogeneous coarsening just by forming a very fine microstructure?
- Is superplasticity good or bad in the thermomechanical fatigue of solders?
- Depending on what effect superplasticity has, what processes are needed to form, or keep from forming, superplastic solder joints?

A question was raised as to what effect does the difference in thermal expansion between the Pb–rich and Sn–rich phases have on the thermomechanical fatigue properties of the solder. The Sn–rich phase has a thermal expansion of $20 \times 10^{-6}$ in/in°C and the Pb–rich phase has a thermal expansion of $29 \times 10^{-6}$ in/in°C. With a difference in expansion of $9 \times 10^{-6}$ in/in°C, could the solder be imposing deformation upon itself during thermal cycling? The effect was discussed and thought to be minor compared with the magnitude of externally imposed strain. However, this effect has not been studied and the results could prove interesting.

Another area that is not well understood is what effect the initial microstructure of the solder joints plays in the thermomechanical fatigue properties. Unfortunately, very few thermomechanical fatigue studies document the initial microstructure of the solder joints. One suggestion that received support was that all solder joints should be significantly aged prior to testing. This initial aging would bring the joints closer to a more stable microstructure and may simulate service conditions. Other workshop participants felt that the initial microstructure was not as important because the microstructure evolves quickly regardless of the starting state. The conclusion was that further work is needed to determine the effect that the initial microstructure has on the thermomechanical fatigue properties of solder joints.
The cracking and final failure of solder joints was discussed in depth with contention. A controversy arose when discussing when the solder joint actually begins to crack (and this is especially true in near eutectic Sn–Pb alloys). One group believes that cracks form in solder joints after the first thermomechanical fatigue cycle, and each subsequent cycle propagates those cracks. The other group believes that cracking occurs well into the thermomechanical fatigue process after a certain degree of microstructural evolution has occurred. The difference in these two opinions could be the degree of resolution. The definition of a crack is not clear—at one extreme cracks exist before the test begins at a fine microstructural scale—at the other extreme a crack exists when electrical continuity is lost. What is first needed is an objective definition of a crack. The importance of this question is clear when the thermomechanical fatigue process is to be modeled to predict failures. Some believe that the thermomechanical fatigue process in solder can be modeled by fracture mechanics and life predicted by only using crack growth rates. This approach is conservative (and may very be overly conservative) if all the life, especially the stage involving microstructural evolution, is ignored before the crack exists. Chapter 8 expands upon this discussion. Therefore the issue is what is an important crack, and when does that crack form?

Some discussion focused on the properties of Pb–rich alloys. The consensus was that the failure of Pb–rich solders in thermomechanical fatigue is void formation at grain boundaries. The voids either coalesce or cracks propagate between the voids. The effect of Sn precipitates in the Pb–rich solders is thought to be minimal due to the propensity for failure at the Pb–rich grain boundaries. Methods to improve the microstructure of Pb–rich alloys are limited. Chapter 6 discusses this.

**Thermomechanical Fatigue and Isothermal Fatigue**

Isothermal fatigue is often used to model the thermal fatigue behavior of solder joints. Isothermal fatigue is generally an easier experiment to perform and a great deal of metallurgical information can be derived from this type of testing. Chapter 4 discusses the observations on the isothermal fatigue behavior of solders in great detail. One of the difficulties in making comparisons between isothermal and thermomechanical fatigue is the limited amount of thermomechanical fatigue data (both microstructural and mechanical) that is available for comparison with isothermal fatigue. The data that is available is on bulk high–Pb content solders and near eutectic Sn–Pb solder joints.

Isothermal and thermomechanical fatigue exhibit a number of similarities and differences, and the following paragraphs discuss these. Note that there is not a great depth of understanding of the relationship between isothermal and thermomechanical fatigue: what exists are simply observations.

**High–Pb Content Solders**

A great deal of work has been performed on the isothermal fatigue of these solders, and Chapter 4 discusses these. Fortunately, the thermomechanical fatigue work by Lawson was performed using techniques similar to those used in isothermal fatigue. It is through Lawson's work, and that presented in Chapter 4, that the following relationships can be derived.
The effect of strain range on the number of cycles to failure for high-Pb solders is the same for both isothermal and thermomechanical fatigue: the higher the strain range, the shorter the fatigue life. When tested in a sawtooth thermal–strain cycle with a period of 240 s/cycle at 25°C to 80°C, the thermomechanical fatigue life of high-Pb content Sn–Pb solders appears to be shorter than the isothermal fatigue life at 80°C. (The shortest life in isothermal fatigue occurs at the highest temperatures.) However, when the deformation rate increases, the thermomechanical fatigue life increases and approaches the isothermal fatigue life. This behavior indicates that mechanisms of deformation and failure include an effect present in thermomechanical fatigue that is absent in isothermal fatigue.

The explanation that has been advanced for the discrepancy in deformation rate effects is that during isothermal fatigue, a decrease in the deformation rate leads to a reduction in the number of cycles to failure due to an increase in the creep that occurs during the longer fatigue cycle. During thermomechanical fatigue, a decrease in the deformation rate leads to an increase in the number of cycles to failure. This indicates that even though the amount of damage due to creep also increases in thermomechanical fatigue, the damage may be annealed out during the temperature cycling. This reasoning is only a hypothesis; further work needs to be performed on high-Pb content Sn–Pb solders for confirmation.

The effect of hold time on the fatigue life of high-Pb content Sn–Pb solders during thermomechanical fatigue is similar to that during isothermal fatigue; the number of cycles to failure is reduced when the hold time is increased, and the limitation in the number of cycles to failure at longer hold times is expected. Thermomechanical fatigue hold time data may be treated similarly to isothermal fatigue hold time data by using methodology described in the previous chapter. It must be emphasized that when the results from hold times of isothermal and thermomechanical fatigue are compared, the holds must be at similar strain levels (such as at the temperature–strain extremes). The relations between the number of cycles to failure and hold time, and between times to failure (total, during ramps and hold) and hold time are depicted in Figures 28 and 29.

Near Eutectic Sn–Pb Solders

A comparison of thermomechanical and isothermal fatigue for near eutectic solders reveals similar results to those described above for high–Pb content solders. Work by Frear and Jones [43] directly compares isothermal and thermomechanical fatigue results. The main conclusion was that the response of near eutectic Sn–Pb solders in thermomechanical fatigue cannot be predicted using isothermal fatigue testing. This is due to the microstructural evolution that occurs in near eutectic solders, and not in high–Pb content solders. In isothermal fatigue, a single mechanism dominates during each test (at low temperatures, a dislocation motion process dominates; at elevated temperatures, diffusional flow is the operative mechanism). For thermomechanical fatigue during each thermal cycle, the deformation mechanism changes from dislocation processes to diffusional flow, and the solder responds to this mechanism change by undergoing the heterogeneous coarsening process that was described earlier.
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Figure 28  Effect of hold time during thermomechanical fatigue on the number of cycles to failure. Plot courtesy of L. R. Lawson.

Figure 29  Ramp time, hold time, and total time to failure for thermomechanical fatigue of high Pb content Sn–Pb solder. A) 0.44% total strain, B) 0.6% total strain.

The other difference between isothermal and thermomechanical fatigue of near eutectic solders is similar to that found for high–Pb content solders: the effect of deformation rate. At slower strain rates, the dislocation substructure recovers faster than it work hardens in thermomechanical fatigue, due to the
temperature deformation mechanism discussed earlier. This response tends to minimize the subsequent recrystallization and heterogeneous growth of the solder microstructure. In isothermal fatigue, the damage accumulates under one mechanism and the material response differs.

Work on the fatigue properties of steels (Chapter 7) has shown that thermomechanical fatigue is much more damaging than isothermal fatigue. This effect is entirely possible in near eutectic solder alloys. Wolverton [17] showed that near eutectic solder joints cycled under conditions of thermomechanical fatigue failed earlier than those mechanically cycled at constant temperature. However, a comprehensive comparison between isothermal and thermomechanical fatigue results is needed.

Summary of Isothermal and Thermomechanical Fatigue Comparisons

The consensus of the participants at the workshop was that isothermal fatigue can be used as a gross comparisons of fatigue life with thermomechanical fatigue. Isothermal fatigue can be used for comparisons of solder alloys, and this ranking could possibly hold true for thermomechanical fatigue conditions. However, extreme care should be taken in trying to directly apply isothermal fatigue results for thermomechanical fatigue situations. For example, there is a different response of solders as a function of strain rate between isothermal and thermomechanical fatigue for both Pb-rich and near eutectic Sn–Pb solders. In isothermal fatigue, as the strain rate decreases, the fatigue life also decreases. However, in thermomechanical fatigue, as the strain rate decreases, the fatigue life increases [40, 41, 43]. This example points out that the microstructure changes and the deformation mechanism can very well be different between isothermal and thermomechanical fatigue environments.

The consensus from the workshop was that more work is needed to determine the relationships between isothermal and thermomechanical fatigue. Until that relationship is established, isothermal fatigue can only be used to make gross comparisons between solder alloys, with possible careful extrapolation of those results to thermomechanical fatigue.

Summary of Needed Future Work

The desired outcome of this chapter was to definitively state the fundamental metallurgical mechanisms involved in the thermomechanical fatigue of solder materials so that these could be incorporated into metallurgically based life predictive models. Unfortunately, the state of understanding of the thermomechanical fatigue behavior of solders is still too immature to sufficiently define all the metallurgical information needed to predict fatigue life from fundamental principles. The following is a summary of areas that need further research to become well defined. These represent a consensus of critical discussions that were held at the Solder Mechanics Workshop.
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TESTING METHODOLOGY

To fully understand the response of solders in thermomechanical fatigue, a fully instrumented test should be used. The test must have a simple (or at least definable) strain state, and mechanical and microstructural data must be obtained. No single method is now available, although the thermomechanical fatigue of solder joints method is currently the best.

There is a strong need to have a consistent definition of failure. Continuous continuity monitoring appears to be the optimal choice, especially from an engineering definition of failure. However, even with this method, it is difficult to extract metallurgical information. What is needed is a definition of failure that can be universally applied so that test results can be compared against a standard reference.

TEST ACCELERATION

For thermomechanical fatigue testing to occur in a relatively short time frame, the tests must be accelerated. Work needs to focus on defining what test conditions can be accelerated and still give meaningful results. The conditions used to accelerate the test must not create the failure mechanisms. Therefore, more understanding is needed on the parameters that accelerate thermomechanical fatigue tests: deformation rate, hold times, and temperature extremes.

FAILURE BEHAVIOR

It is well accepted that the failure mechanism in high–Pb content Sn–Pb solders is intergranular cracking. However, the failure mechanism in near eutectic Sn–Pb solders is not as well defined. Some researchers believe that solder joints crack on the very first thermal cycle, or cracks are initially present in the microstructure that propagate on the first cycle. Others believe that a heterogeneous coarsening process precedes failure. Experiments are needed to determine when cracks occur in solder alloys and how to define a crack.

If the failure mechanism in near eutectic Sn–Pb solders is preceded by a heterogeneous coarsening process, a number of questions remain unanswered concerning the nature of the heterogeneous coarsened region. Is the heterogeneous coarsened band superplastic? Are solder joints without the heterogeneous coarsened band superplastic to begin with? It is unknown whether superplasticity is good or bad under the conditions of thermomechanical fatigue. Furthermore, there is little or no information available about the fatigue behavior of superplastic materials. This information is needed to help us understand the thermomechanical fatigue behavior of the heterogeneous coarsened regions.

It is also not known where cracks propagate through the solder joint once they initiate. Cracks are observed through the Sn regions, the Pb regions, and at phase boundaries; detailed study is needed for this problem.
MICROSTRUCTURAL EFFECTS

It is unknown what effect the differing thermal expansion of the Pb and Sn phases have on each other under conditions of thermomechanical fatigue. Does the solder impose deformation upon itself? This may be a secondary effect, but should be defined.

A detailed study on the effect of the initial microstructure of solder alloys under conditions of thermomechanical fatigue is needed. There is some question as to whether there is an effect at all, because the solder microstructures evolve so quickly; this needs to be determined.

EFFECT OF INTERMETALLICS IN THE SOLDER JOINT

The effect intermetallics have on the thermomechanical fatigue behavior of solder joints is unknown. Research must be performed to determine if joints fail as a result of the presence of intermetallics, and under what conditions.

ENVIRONMENTAL EFFECTS

Work on high-Pb content Sn–Pb solders has shown that the environment of air and water has a large effect on the thermomechanical fatigue behavior by significantly shortening the lifetime. However, it is not known whether there is an effect of environment on the thermomechanical fatigue behavior of near eutectic Sn–Pb solders (or any of the other solder alloys). It is possible that the environment could have a very large effect because Sn is known to be even more reactive than Pb. Also, there is an hypothesis that the mechanism of failure in solders is crack initiation at oxide particles. The environmental effects need to be characterized for solder alloys.

THERMOMECHANICAL AND ISOTHERMAL FATIGUE

It is recognized that isothermal fatigue does a poor job of predicting thermomechanical fatigue behavior of solders. However, there is a large amount of isothermal fatigue data available. There is a need to perform careful, systematic testing of both isothermal and thermomechanical fatigue to determine the limitations of comparing the two, and what correlations are valid.

OTHER SOLDER ALLOYS

There is little or no information at all about the thermomechanical fatigue behavior of solders that are not Sn–Pb based. These studies must be performed because there are solders that appear to have better thermomechanical fatigue properties than Sn–Pb, and these alloys are being used as replacements without being fully understood.

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