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Fatigue and Thermal Fatigue Testing of Pb-Sn Solder Joints


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In an electronic package, materials of different thermal expansion coefficients are usually joined with Pb-Sn solder. The combination of temperature fluctuations and different thermal expansion coefficients creates a condition of thermal fatigue in the solder joints. This paper presents a discussion of experimental techniques developed to study fatigue in solder joints. Specimens have been developed to reproducibly test solder joints in shear using a modified double lap shear configuration. Tests were performed using a digital loadframe especially designed to isothermally fatigue solder joints in shear. Joints tested had a nominal solder composition of 60Sn-40Pb soldered to Cu. Failures were found to occur in the solder joint after fewer cycles at 125°C than at lower temperatures. Solder joints were also tested in shear thermal fatigue. A specimen design consisting of two materials with different thermal expansion coefficients constraining a solder joint was cycled between -55°C and 125°C. Results of these tests indicate that there is a coarsening of the solder near the joint interface and fatigue cracks initiate in these coarsened regions.
INTRODUCTION

Pb-Sn SOLDERS are commonly used in the electronics industry to join components of electronic packages. The solder not only acts as an electrical connection between components but also as a mechanical bond to join, for example, a chip carrier to a printed circuit board. In service electronic packages are exposed to thermal fluctuations caused by environmental changes (-55°C to 125°C). These thermal fluctuations combined with the materials in the package that have different coefficients of thermal expansion lead to a condition of low cycle thermal fatigue. A schematic diagram illustrating thermal fatigue in shear is shown in Figure 1. Failures in solder joints have been observed in electronic packages after a number of thermal cycles2-5. The integrity of the solder joints is essential. The failure of one joint could render the chip, or an entire system, inoperable. The critical nature of the solder joints demands fundamental understanding of how and why failures occur.

This paper describes new experimental techniques developed to study solder joints in low cycle fatigue. These procedures were designed to relate the mechanical properties of solder joints to the joint microstructure. Accelerated low cycle fatigue tests were performed by mechanically imposing, at constant temperature, an external reversible shear strain on a solder joint. This testing procedure, referred to as isothermal fatigue, tests solder joints at various temperatures. Low cycle thermal fatigue tests were performed by cycling solder joints from -55°C to 125°C. The different thermal expansion coefficients of the materials constraining the joint result in a shearing strain on the joint. Some results and microstructural observations of both of these fatigue tests are presented and discussed.

ISOThERMAl FATIGUE

SPECIMEN DESIGN - To perform isothermal fatigue tests in shear it was first necessary to develop a specimen to reproducibly fatigue solder joints in shear. Specimen designs have been described in the literature6 for testing solder joints in shear. Some of the more common designs are discussed below.

Single Lap Shear: This specimen design is illustrated in Figure 2a. The specimen consists of two plates soldered together then strained in a direction parallel to the joint. Initially the joint is in simple shear but after a small amount of strain a moment arm develops in the joint causing the joint to deform out of shear. The deformation of the joint is not in shear and would therefore give results that can not be interpreted.

Double Lap Shear: This design is illustrated in Figure 2b and consists of three plates soldered together in two joints. The addition of the third plate in this design balances out the moment arm present in the single lap shear specimen allowing both solder joints to experience simple shear deformation. Practical difficulties arise in the manufacture of the solder joints in this design. Usually joints are soldered individually and the different joint thermal histories causes variances in microstructure which, in turn, affect joint behavior. Work by Thwaites6 reports a large variance in the mechanical properties of these solder joints tested under identical conditions. It appears that this specimen fabrication is not reproducible.

Ring and Plug- This design consists of a rod soldered into a sleeve, Figure 2c. The joint gap is created by the insertion of wires between the ring and plug. Friction holds
the ring and plug together during immersion into the molten solder. This design does permit simple shear testing of the solder joint. However, the presence of wires in the solder joint can act as initiation sites for failures during fatigue testing. Additionally, this design does not allow for direct observation of the joint during testing, sections must be cut through the specimen. Thwaites\textsuperscript{6} found that the joint strength when the plug is pulled through the ring is significantly different than when it is pushed. This fact, combined with the difficulties in making observations of the deformed joint, indicates that this specimen design is unsuitable for fatigue testing.

Modified Double Lap Shear: A schematic diagram of this specimen designed for this work is shown in Figure 3. The specimen consists of three Cu plates soldered together forming two joints. Three rounded holes are machined into the Cu to isolate joints in the middle of the specimen. Friction grips are affixed to the top and bottom portions of the specimen. By displacing the specimen vertically both solder joints experience simple shear. A special technique was developed to manufacture the above specimens in a reproducible manner. Three Cu plates were machined to the dimensions shown in Figure 4 polished, etched, and lightly fluxed before assembly. Stainless steel spacers were inserted next to the bolts to provide a gap for the joint. The assembly was then placed in the two stage vacuum furnace diagrammed in Figure 5. The Cu assembly and solder were heated simultaneously to 50°C above the melting point of the solder. The heating was performed under vacuum allowing the flux to evaporate from the Cu surface leaving a clean, oxide free surface. On immersion of the assembly into the molten solder capillary action pulls the solder into the joint gaps. The assembly and solder is then rapidly cooled to room temperature. Fatigue test specimens are machined from the soldered assembly. Each assembly yields 7-10 specimens. Specimens from each assembly experienced identical processing thereby minimizing variations between specimens. The specimens themselves experience simple shear in fatigue testing and the deformation process is easily observed in this configuration.

**DIGITALLY CONTROLLED LOADFRAME** - In order to test the double lap shear solder joints in fatigue it was necessary to design a loadframe capable of testing solder joints in various thermal environments with extremely small elongations and strain rates. The loadframe designed for these tests is shown in Figure 6. The machine consists of a compression tube\textsuperscript{*}, a stepper motor that activates the pullrod and a digital microprocessor that controls the stepper motor.

The digital nature of this loadframe allows for versatility and accuracy in control features (such as strain rate and total strain in low cycle fatigue). The computer allows for either analog (chart recorder), or digital data collection. The compression tube makes it possible to test solder joints at various temperatures by immersing the compression tube in an environmental bath.

\textsuperscript{*}The compression tube actually consists of three ground surface finish rods that exactly align the pullrod to the specimen. This allows the specimen to remain aligned during deformation so no out of plane buckling can occur.
ISOTHERMAL FATIGUE RESULTS - Low cycle fatigue tests were performed on double shear specimens. The total strain imposed on each specimen and the testing temperature were varied. Specimens consisted of Cu plates in the modified double lap shear configuration using 60Sn-40Pb solder. The solder joint thickness was 0.51 mm (20 mils), and the deformation rate was a constant .05mm/min. Specimens fatigued at 35% strain failed after 6 cycles at 125°C while specimens tested for the same strain at -55°C did not fail after 150 cycles. Direct observation of the joint tested at 125°C is shown in the SEM micrograph of Figure 7 and reveals extensive cracking on the surface of the solder. A plot of the number of cycles to failure versus strain imposed in isothermal fatigue as a function of temperature is shown in Figure 8. The number of cycles to failure increases with decreasing temperature and decreasing strain.

THERMAL FATIGUE

In order to understand the combined effects of strain and temperature on the solder joint microstructure, thermal fatigue tests in shear were performed. The specimen used for thermal fatigue testing is shown in Figure 9. The design consists of two solder joints joining materials with different thermal expansion coefficients (α). For this experiment the materials used were:

\[
\begin{align*}
\text{Cu} & \quad \alpha = 25 \times 10^{-6} \degree \text{C} \\
\text{Al} & \quad \alpha = 16.6 \times 10^{-6} \degree \text{C}
\end{align*}
\]

The Al plate was electroplated with Ni (diffusion barrier) and then plated with Cu so the solder would join with Cu on both sides of the joint. The assembly was manufactured in the vacuum furnace as described previously. Individual specimens were cut from the assembly. By cycling this specimen between two temperatures a shear strain was developed. The strain magnitude, however, varies from zero in the center of the specimen to a maximum at the two ends.

To perform the thermal cycling an automatic testing apparatus was built and is shown in the schematic diagram in Figure 10. The apparatus consists of a high and low temperature thermal baths: 125°C (±1°C) resistively heated silicon oil, -55°C (±5°C) an ethyl alcohol medium cooled by a continuous flow of liquid nitrogen through a copper coil submerged in the bath. The liquids allow for rapid heat transfer to the specimens and minimize exposure to oxidizing effects of the atmosphere. A digitally controlled crane transferred the specimens in the basket between the baths. A hold time of 5 minutes in each bath was selected and the transfer time between baths was 30 seconds.

OBSERVATIONS IN THERMAL FATIGUE - Tests were performed up to 1300 cycles. Figure 11 shows the development of the solder joint microstructure with the number of cycles. A coarsened region develops in the Pb-Sn solder joint after 275 cycles and grows with increasing number of cycles. The coarsened region develops as a function of strain. At the center of the specimen where there is no strain during testing no extensively coarsened region is observed. In the later stages of thermal cycling, after 1000 cycles, cracks develop in the coarsened region. These cracks eventually lead to the final failure of the solder joint, as can be seen in the specimen after 1300 cycles. The cracks appear to initiate in the Sn-rich areas and then propagate through the Pb-rich areas, Figure 12.
CONCLUSIONS

ISO THERMAL FATIGUE - A modified double lap shear specimen design and manufacturing technique was presented to reproducibly test solder joints in low cycle isothermal fatigue. A special digital loadframe was designed to fatigue the double shear specimens. Failures were observed to occur in a region adjacent to the solder/Cu interface. The number of cycles to failure increased with increasing temperature and increased strain.

THERMAL FATIGUE - A special specimen was designed consisting of Cu and Al plates (two materials with different coefficients of thermal expansion) constraining a 60Sn-40Pb solder joint. A digitally controlled crane cycled these specimens between -55°C and 125°C. After 275 cycles a coarsened region developed in the solder joint near the joint interface. The coarsened region only occurs when strain is imposed during thermal fatigue. Cracks occur in the coarsened region of the joint after 1000 cycles leading to the complete failure of the joint.

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REFERENCES

1) Military Standard MIL-STD-883B
Origin of Thermal Fatigue

Figure 1 Origin of thermal fatigue between an alumina chip carrier and a polyimide circuit board.
Fig. 2 Solder Joint Designs

a) b) c)

$t = \text{solder joint thickness (0.25mm)}$
$d = \text{joint overlap (10mm)}$

Figure 2 Solder joint specimens.
Figure 3 Modified double lap shear specimen.
Figure 4 Specimen assembly design before soldering.
Figure 5  Schematic diagram of vacuum furnace for manufacture of solder joints.
Figure 6 Digital loadframe with computer and electronics designed to test solder specimens in low cycle fatigue.
Figure 7  SEM micrograph of a solder joint after isothermal fatigue at 125°C.
Figure 8 Plot of number of cycles to failure versus testing temperature, as a function of strain, in isothermal fatigue.
Figure 9 Specimen design to test solder joints in shear during thermal fatigue.
Figure 10 Testing apparatus to automatically cycle specimens between two thermal baths.
Figure 11 Development of solder joint microstructure with number of cycles.
Figure 12 Solder joint after 1300 cycles with fatigue cracks propogating through the Sn (light phase).
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