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ABSTRACT

This paper presents a fundamental investigation of the fatigue and thermal fatigue characteristics, with an emphasis on the microstructural development during fatigue, of Sn-Pb solder joints. Fatigue tests were performed in simple shear on both 60Sn-40Pb and 5Sn-95Pb solder joints. Isothermal fatigue tests show increasing fatigue life of 60Sn-40Pb solder joints with decreasing strain and temperature. In contrast, such behavior was not observed in the isothermal fatigue of 5Sn-95Pb solder joints. Thermal fatigue results on 60Sn-40Pb solder cycled between -55°C and 125°C show that a coarsened region develops in the center of the joint. Both Pb-rich and Sn-rich phases coarsen, and cracks form within these coarsened regions. The failure mode of 60Sn-40Pb solder joints in thermal and isothermal fatigue is similar: cracks form intergranularly through the Sn-rich phase or along Sn/Pb interphase boundaries. Extensive cracking is found throughout the 5Sn-95Pb joint for both thermal and isothermal fatigue. In thermal fatigue the 5Sn-95Pb solder joints failed after fewer cycles than 60Sn-40Pb.

INTRODUCTION

Sn-Pb solder joints are used extensively in the electronics industry as an electrical/mechanical interconnection in electronic packages. A major requirement of the solder joints is that they absorb strains arising from thermal expansion mismatch of unlike materials within the package. For instance, the mismatch between a polyimide circuit board and a leadless ceramic chip carrier (or between a Si chip and the ceramic carrier) produces a shearing strain on the solder joints when the package encounters thermal fluctuations. These temperature fluctuations arise from both enviromental and power cycling. The large fluctuating shear strains create cracks in the solder joint and lead to early catastrophic failures (1-3). Therefore, there is a significant need to better understand the fatigue and thermal fatigue properties of the solders used in electronic packaging.

The purpose of this study is to investigate the fatigue and thermal fatigue characteristics of Sn-Pb solder joints and to relate these results to the microstructural mechanisms that determine fatigue life. Previous work on the Sn-Pb system in conditions of isothermal fatigue (4-9), fatigue at constant strain and temperature, were performed on bulk solder or in various designs of solder joint test specimens. Thermal fatigue tests were performed directly on the solder joints in electronic packages (10-24). However, a correlation between the two fatigue conditions is lacking. This paper presents results of a study of two commonly used Sn-Pb alloys, 60Sn-40Pb and 5Sn-95Pb, soldered to Cu surfaces. These solders were studied in a joint configuration in conditions of thermal fatigue and isothermal fatigue with an emphasis on the microstructural development during fatigue.

EXPERIMENTAL PROCEDURE

Special techniques for the manufacture and fatigue testing of solder joints have been developed in this laboratory and are briefly described here. A more detailed discussion is presented elsewhere (25).

The double shear specimen used to test solder joints in isothermal fatigue is shown in Figure 1a. The two solder joints between the holes experience simple shear on loading along the long axis. The specimen used to test solder joints in thermal fatigue is shown in Figure 1b. The specimen consists of an Al plate ($\alpha = 25$ ppm/°C) sandwiched between two Cu plates ($\alpha = 16.6$ ppm/°C). The Al was plated with 0.05 mm (0.002 in) of Ni to act as a diffusion barrier, and 0.025 mm (0.001 in) of Cu to give the solder joint a similar interface on each side. On thermal cycling, the solder joints between the Cu and Al plates undergo simple shear deformation.

To manufacture solder joint specimens, an assembly of plates were bolted together with the appropriate spacers to form a gap, Figure 2. The assembly was submerged in a molten solder bath, in vacuum, and then cooled. Individual specimens were then cut from the assembly. This insures microstructural consistency between test specimens within the same block. Each block yields 8-10 specimens. The solders were made using 99.99 pure Sn and 99.9 pure Pb.

Isothermal tests were performed on a digitally controlled loadframe. Tests were performed at -55°C (ethyl alchohol cooled by liquid nitrogen), 0°C (ice water), room temperature, and 125°C (quench oil). A through-cracked joint was consistently associated with a 30% decay in cyclic load amplitude. This 30% decay was then used to define the number of cycles to failure. A constant strain rate of 0.05 mm/min was used. The cycling frequencies for the total strains imposed were as follows:

35% strain = 8.4 cycles/hour,
30% strain = 9.8 cycles/hour,
25% strain = 11.8 cycles/hour,
20% strain = 14.8 cycles/hour.

Thermal cycling tests were performed by cycling the specimens between two thermal baths, one at -55°C the other at 125°C. The hold time in each bath was 5 minutes with a transfer time of 30 seconds. The use of liquid thermal baths has two advantages: 1) a rapid heat transfer between the specimen and the bath, 2) an inert atmosphere that eliminates oxidation, which is known to decrease the fatigue life of solder (10).

In the Scanning Electron Microscope (SEM), contrast of the Pb-rich phase is light and the Sn-rich phase dark, in optical micrographs the Pb-rich phase is dark and the Sn-rich phase light.

RESULTS

Initial Microstructure

The initial microstructure of the 60Sn-40Pb on Cu solder joint is shown in Figure 3. The solder consists of globular Pb-rich and Sn-rich phases mixed in with Pb-rich dendrites and eutectic lamellae. The interfacial structure, Figure 4, is a two phase intermetallic Cu_6Sn_5 adjacent to the solder and Cu_3Sn adjacent to the Cu. In the bulk of the solder intermetallic Cu_6Sn_5 whiskers are also observed (26), Figure 5. The microstructure of 95Pb-5Sn is shown in Figure 6 and consists of a Pb-rich matrix with a distribution of ß-Sn precipitates (27-28). A Cu_3Sn intermetallic forms at the interface between the 5Sn-95Pb and Cu (29), Figure 7.

Isothermal Fatigue

Isothermal fatigue tests were performed on solder joints in shear to investigate the function of temperature and total amount of shear strain on the microstructure and failure characteristics of both 60Sn-40Pb and 95Pb 5Sn solder joints. The results of the fatigue tests on 60Sn-40Pb joints are shown in Table I. A plot of this data in percent total strain vs. cycles to failure with varying testing temperature is shown in Figure 8. The number of cycles to failure increases with decreasing temperature and decreasing strain. The effect of strain on cycles to failure is not strong at 125°C. Figure 9 shows a failed 60Sn-40Pb solder joint, in cross section, cyclically strained at 35% and 125°C. Extensive cracking is found along the grain boundaries in the Sn-rich phase and at the interphase boundaries. Little cracking is observed to occur within the Pb-rich phase. The microstructure of 60Sn-40Pb solder joints tested at lower temperatures and smaller strains show cracking through the Sn- rich phase but not to the same extent as at higher temperatures.

The results of the isothermal fatigue tests on 5Sn-95Pb solder joints are shown in Table II. This data shows no correlation between temperature, strain and the number of cycles to failure for the 5Sn-95Pb solder joints. Furthermore, the 5Sn-95Pb solder joints fail sooner than 60Sn-40Pb at temperatures below 20°C. At 125°C both solders fail after a similarly short number of cycles. The microstructure of a failed 5Sn-95Pb joint at 125°C and 30% strain is shown in cross section in Figure 10. Extensive cracking throughout the solder is observed both parallel and perpendicular to the direction of shear, and takes on a mosaic structure throughout the joint. This failure mode is observed at all temperatures and strains in the isothermal fatigue tests.

Thermal Fatigue -55°C to 125°C

Thermal cycle tests were performed on 60Sn-40Pb solder joined to Cu and Al plates. The joint thickness tested was 0.254 mm (10 mil). The resultant shear strain at the ends of the specimen when cycled between -55°C and 125°C was 14%. A series of cross section optical micrographs taken of different specimens during the fatigue process between -55 °C and 125°C is shown in Figure 11. After 625 cycles a thin coarsened region develops through the center of the solder joint. In this region, both the Sn-rich phase and Pb-rich phase coarsen, Figure 12. Figure 11 reveals that after 1000 cycles cracks are present in the coarsened region, specifically along the grain boundaries of the Sn-rich and the interphase boundaries (Figure 13). In all cases the cracks were found solely in the coarsened region.

Thermal Fatigue: 95Pb-5Sn

Thermal cycle tests were also performed on 95Pb-5Sn solder joints between Cu and Al plates. The specimens were cycled from -55°C to 125°C. The resultant microstructures are summarized in the SEM micrographs of Figure 14. Cracks form after only 120 thermal cycles. Extensive cracking was found in the joint at 250 and 500 thermal cycles. The cracks run both parallel and perpendicular to the joint. The mosaic failure pattern was observed in both thermal and isothermal fatigue of 5Sn-95Pb. This is clearly apparent in the specimen after 120 thermal cycles, Figure 15.

DISCUSSION

In isothermal fatigue the number of cycles to failure at room temperature and below is less for 5Sn-95Pb than for 60Sn-40Pb. At 125° the number of cycles to failure is similar for both alloys. The fatigue properties for 60Sn-40Pb deteriorate at 125°C as a consequence of the extensive intergranular cracking in the Sn-rich phase. At lower temperatures many more cycles are required to achieve the same extent of cracking in the Sn-rich phase, and therefore longer isothermal fatigue lives. In contrast, 5Sn-95Pb fails in isothermal fatigue after a short number of cycles for all temperatures tested, and does not display this degradation of fatigue properties.

The thermal cycling tests indicated that 60Sn-40Pb solder has a much longer thermal fatigue life than 5Sn-95Pb. An interesting observation from the thermal fatigue tests of 60Sn-40Pb solder joints is the localized coarsening of both the Sn and Pb-rich phases. In addition to this, cracks were found to form solely within these coarsened regions.

Within a given solder compositio, the isothermal and thermal fatigue failure modes were similar. For the 5Sn-95Pb solder joints, a mosaic failure pattern was found for both tests. In the 60Sn-40Pb cracks form intergranularly within the Sn-rich phase and at the Sn phase/Pb phase boundary.

SUMMARY AND CONCLUSIONS

Isothermal fatigue tests to failure were performed on both 60Sn-40Pb and 5Sn-95Pb solder joints at temperatures between -55°C and 125°C and shear strains from 20% to 35% shear strain. The number of cycles to failure for the 60Sn-40Pb joints increased with decreasing strain and temperature. The 5Sn-95Pb joints showed a fatigue life that could not be correlated with strain and temperature in the ranges tested. At temperatures below 20°C the 5Sn-95Pb solder joints failed after fewer cycles than 60Sn-40Pb joints. At 125°C both solder joints failed after a short number of cycles. Thermal fatigue tests of 5Sn-95Pb and 60Sn-40Pb solder joints cycled from -55° to 125°C were performed. The 60Sn-40Pb joints developed a localized coarsening along the length, through the center of the joint, and through both the Pb-rich and Sn-rich phases. Cracks formed only within these coarsened regions after 1000 thermal cycles. However, failures were observed after only 120 thermal cycles for the 5Sn-95Pb solder joints. The results from thermal fatigue indicate that the 60Sn-40Pb solder joints are more fatigue resistant than 5Sn-95Pb solder joints in cycling from -55° to 125°C.

Within a given solder composition, the same fatigue failure mode was found in both isothermal and thermal fatigue tests. The failure mode of 5Sn-95Pb was a homogeneous mosaic crack pattern throughout the joint. In contrast, in 60Sn-40Pb cracks intergranularly in the Sn-rich phase and along the interphase boundaries.

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Table I

Cycles to Failure

Isothermal Fatigue

60Sn-40Pb

	125°C	25°C	0°C	-55°C
$\gamma_{35\%}$	10	75	130	1100
$\gamma_{30\%}$	25	125	215	
$\gamma_{25\%}$	60	425	560	
$\gamma_{20\%}$	55	1450	2300	

Table II

Cycles to Failure

Isothermal Fatigue

95Pb-5Sn

	125°C	25°C	0°C	-55°C
$\gamma_{35\%}$	45	70	60	45
$\gamma_{30\%}$	70	60	95	35
$\gamma_{25\%}$	80	85	230	
$\gamma_{20\%}$	80	60	200	

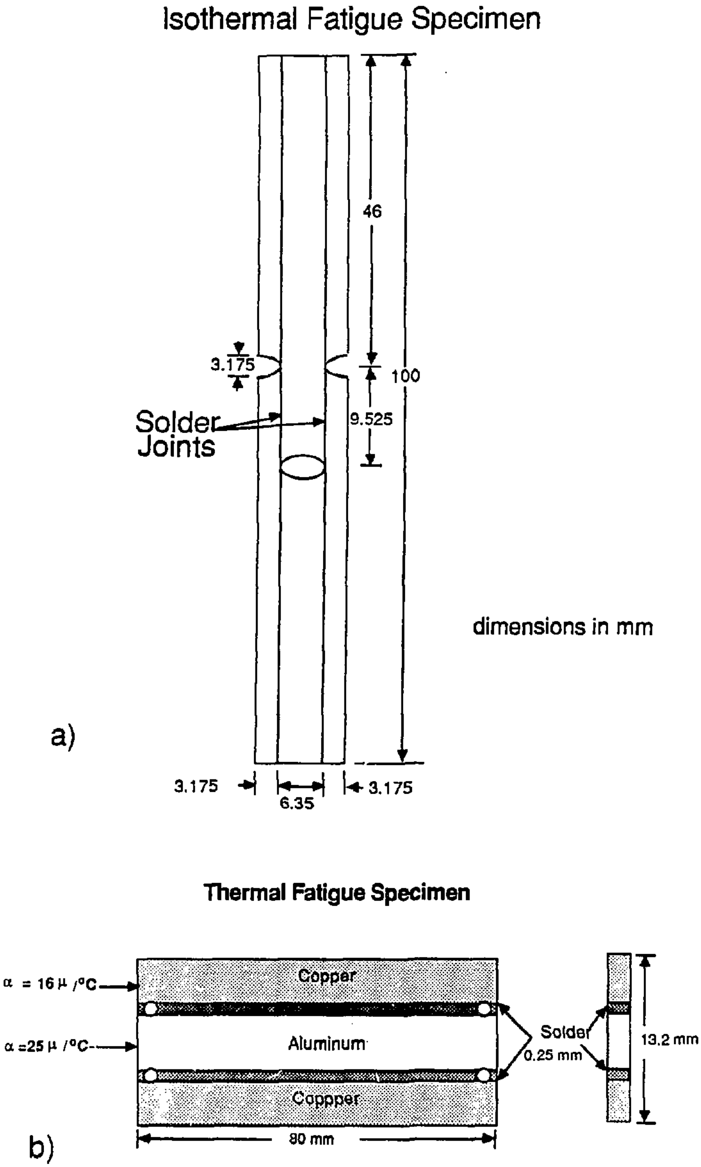

Figure 1 - Specimens used to test solder joint in fatigue. a) Isothermal fatigue specimen. b)Thermal fatigue.

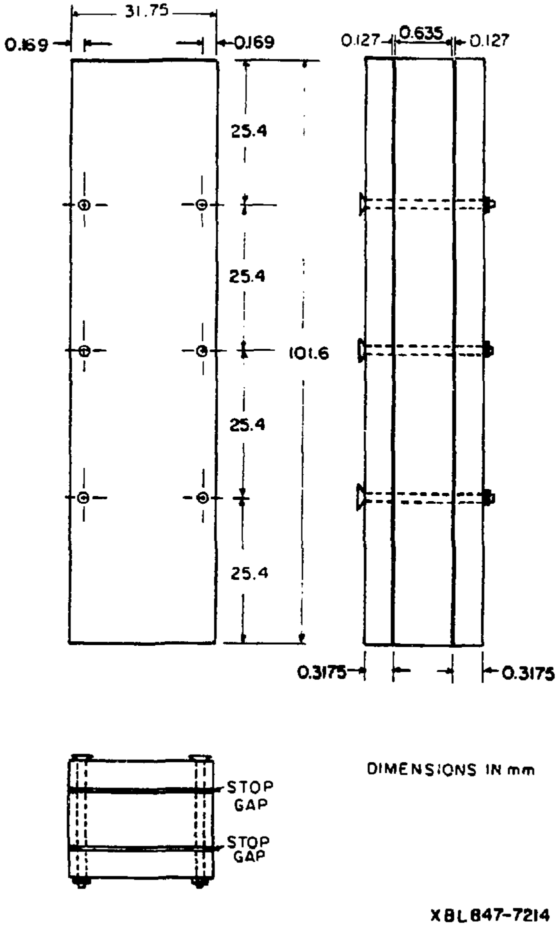

Figure 2 - Assembly of plates used to manufacture solder test specimens.