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Electronic Packaging에 쓰이는 공정 조성의 Pb-Sn Solders에서 Grain Boundary Sliding과 관련된 계면파괴현상

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INTERGRANULAR FAILURE ASSOCIATED WITH GRAIN BOUNDARY SLIDING IN Pb-Sn EUTECTIC SOLDERS USED FOR MICROELECTRONICS APPLICATIONS

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초 록 Pb-Sn eutectic bulk specimens을 thermal cycling동안 electronic package의 땜납이 겪게되는 변형 조건 즉 $10^{-3}-10^{-5}$/s 정도의 낮은 frequency와 0.2−1% 정도의 적당한 strain range에서 피로파괴 실험을 했을때, grain boundary sliding과 관련하여 임계면을 따라 일어나는 균열이 5단계에 의해 묘사될 수 있다는 것을 보였음.

Abstract This report details the microscopic aspects of grain boundary cracking in Pb-Sn eutectic during displacement-controlled mechanical tests performed over a range of low frequency ($10^{-3}-10^{-5}$/s) and moderate strain range (0.2−1%) where is the most technologically relevant to solder joints subjected to thermal cycling. It is shown that intergranular cracking begins with the appearance of crack-like features (CLF's), which can be seen due in part because they are associated with grain boundary sliding, and is able to be described by certain stages of isolated crack growth. In the initial stages CLF's are not ture cracks but instead what I shall call "proto-cracks" where grain boundary sliding begins to damage the grain boundary at the surface. At some point during the initiation stages once proto-cracks become ture cracks, they develop into isolated cracks and the growth of isolated cracks is eventually accomplished by coalescence, resulting in 5 stages of cracking.

Introduction

In my previous report[1,2] leading up to this work, solder joints were thermal-cycled to mechanical failure, then examined for evidence of cracks and other types of microstructural "damage" such as recrystallization of the solidification structure. Grain boundary cracks were oberved as well as recrystallization. The former had been expected based on high temperature fatigue of other alloys[3], whereas the latter had been reported in Pb-Sn solders by a number of previous authors[4~8]. However, while it is clear that intergranular cracks result from the "creep-fatigue interaction", precisely how they initiate and grow in these alloys remains unclear. For these reasons, this report details certain stages of intergranular cracking in the Pb-Sn eutectic during low cycle fatigue at high homologous temperature.

Experiments

Ingots of Pb-Sn eutectic with 99.99% purity obtained from Indium Corporation of America were cast in dog bone-shaped Al molds. Gage sections of fatigue specimens were 3.0mm thick, 10mm wide, and 7.5mm long. All of the specimens studied had wavy microstructures, which is intermediate between lamellar and globular. Typical lamellar spacings, in regions where the microstructure most closely resembles a lamellar structure, were about 1-3 ㎛. The grain sizes and shapes in the cast specimens were uniform. The microstructure was equiaxed or diamond-shaped.

Mechanical testing was performed at room temperature in a screw-driven machine, an Instron floor model 1114 with fine-pitched screws. Fatigue experiments were performed using a constant rate of crosshead motion (stroke control). A symmetric, triangular waveform was utilized. During the test, load was monitored continuously. Strain was monitored as well. Strains were estimated by using linear voltage differential transformers (LVDT's). A 500 pound load cell (Lebow model #829) was used to monitor load. Time, load, and displacement were recorded with a personal computer-based data acquisition system employing 5-1/2 digit Kiethley voltmeters through an IEEE interface. See Fugure 1.

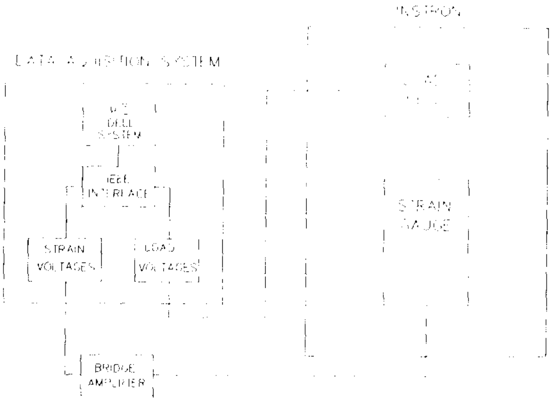

Fig. 1. A schematic drawing showing how Time, load, and displacement were recorded with a personal computer-based data acquisition system employing 5-1/2 digit Kiethley voltmeters through an IEEE interface.

It was discovered, as detailed below, that at low frequencies($10^{-3}-10^{-5}$/s) and low strain ranges($2-1\%$), cracks initiate on grain boundaries on the surface of the specimen. This discovery made it possible to view, in situ (albeit with limited resolution), crack initiation and propagation by using an optical microscope. An optical microscope, salvaged from a discarded Tukon Microhardness Tester, was attached to the Instron. The microscope could be used at magnifications of 100X and 300X and its position could be adjusted by means of micrometer stages.

Results

Incubation

It was observed that there existed a certain period before a CLF appeared along a grain boundary. Incubation period was about 100 cycles during fatigue test at a frequency and strain range (1.6×10^{-3}/s and 0.5%). In the early stages of crack initiation, SEM examination that much of the contrast giving rise to a CLF is due to grain boundary sliding as shown in Figure 2. Thus, it is believed that incubation time corresponds to a period required for a grain boundary to have enough contrast associated with the grain boundary sliding.

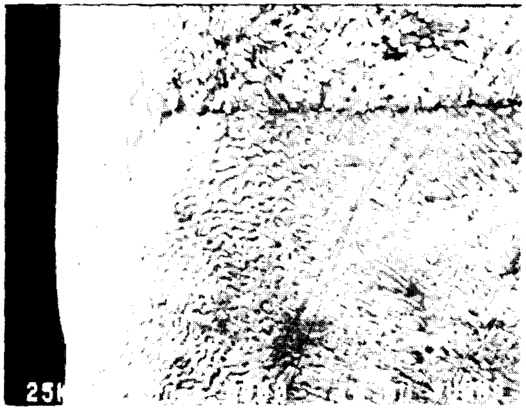

Fig. 2. A scanning electron micrograph of what appeared to be grain boundary cracks under the optical microscope.

Isolated crack initiation

Cracks were observed to initiate at boundaries located on the corners of the specimen. An isolated crack at the corner of the specimen is shown in Figure 3. The boundary intersects the surface at angles of about 45 degrees with respect to the tensile axis, suggesting the importance of grain boundary sliding in the crack initiation process.

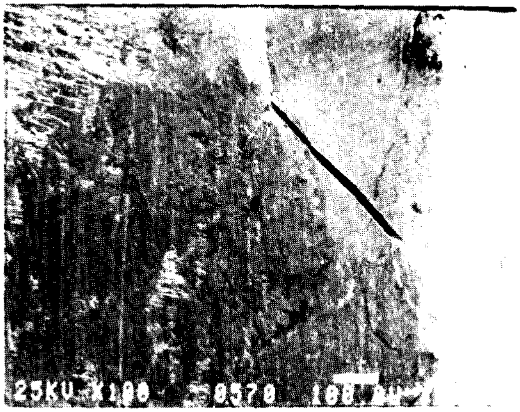

Fig. 3. Fatigue specimen showing the crack initiation at the corner where it undergoes the maximum tensile displacement.

Isolated crack growth

Generally, when a CLF was observed on a grain boundary, the contrast was relatively uniform along the length of the boundary. Therefore, when a new crack appeared along a grain boundary, it was observed that it popped in along the entire length of the boundary, rather than grow gradually along the boundary, resulting in the growth of isolated crack. Figure 4 shows the growth of isolated crack.

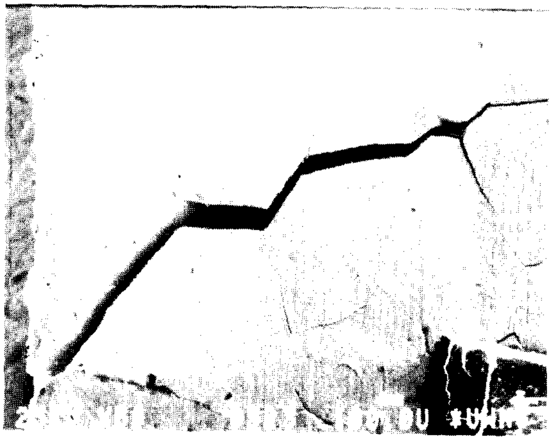

Fig. 4. A scanning electron micrograph showing the growth of isolated crack

Coalescence

Based on the optical microscope, it was observed that the propagation of isolated cracks along adjacent grain boundaries was accomplished by coalescence. Figure 5 displays crack growth associated with coalescence. Coalescence was observed to occur over a relatively short period of about 100 cycles after growth under isolation for longer period, about 1000 cycles.

Fig. 5. A scanning electron micrograph showing crack growth associated with coalescence.

Large crack growth

The investigation about the growth of large cracks in this work was based on failed specimens. Figure 6 shows that large cracks follow the grain boundaries. The front of these

Fig. 6. A scanning electron micrograph showing a failed specimen tested at a frequency and strain range(1.6×10^{-3}/s and 0.5%).

cracks must frequently change direction during as it encounters triple points of the grain boundaries.

Discussion

Clearly, there are significant advantages in being able to monitor crack growth in-situ. However, to view cracks with the optical microscope during fatigue poses two potential limitations. One limitation is the inability to distinguish between cracked boundaries and boundaries that have undergone sliding but have not yet developed cracks. The second potential limitation lies in the possibility that small cracks might be missed.

To test applicability of the optical microscope, when a specimen was fatigued until CLF's could be detected, a close-up of a CLF is shown in Figure 7. In this close-up, the grain at the bottom of the micrograph has moved relative to the grain at the top, toward the observer due to sliding. There are some small cracks associated with the grain boundary sliding, but one must conclude that, especially in the early stages of crack initiation, much of the contrast giving rise to a CLF is due to grain boundary sliding and not cracking. It is also shown in Figure 8 that during sliding, small cracks develop at boundaries between the Pb and Sn phases at and near the surface of the specimen. These cracks are generated at stress concentrations resulting from the roughness of the boundary and might be accelerated in the presence of oxygen because the oxygen can introduce not only a type of stress corrosion phenomenon but also act to prevent the surfaces of the cracks from welding together during the compression part of fatigue.

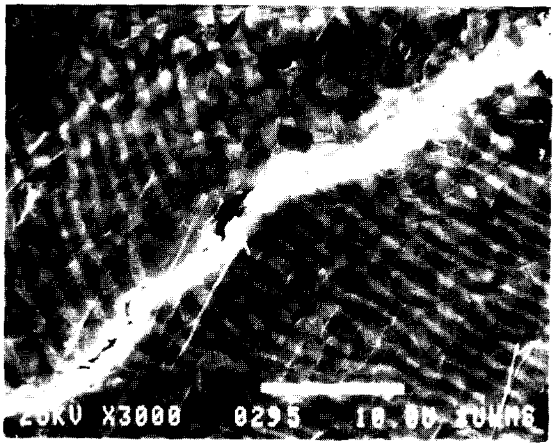

Fig. 7. A scanning electron micrograph showing a close-up of a CLF.

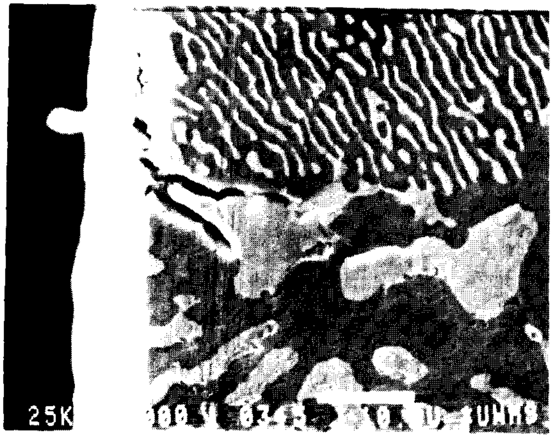

Fig. 8. A scanning electron micrograph showing the cross-section of the crack initiated on sliding grain boundaries.

What conclusions do I draw from the experimental observations shown in the results? First, during the early stages of fatigue the CLF's do not represent ture cracks but instead are types of "protocracks" whose true natures we do not yet understand. All I know is that both sliding and cracking are present, and that the CLF's eventually develop into cracks. Second, it is believed that isolated crack growth and coalescence, as witnessed in the optical microscope, truly reflects a discrete character in the advance of the cracks due to pinning of the crack tip at triple points of the grain boundaries.

Conclusion

In the initial stages of fatigue crack-like features (CLF's) appeared along the entire length of boundaries associated with grain boundary sliding and these CLF's developed into isolated cracks. Then, the pinning of the crack tip at triple points has led to isolated crack growth associated with coalescence. Finally, the growth of large cracks resulted in intergranular failure in eutectic solders. Thus, intergranular cracking in eutectic solders can be described as 5 stages of cracking.

- Incubation
- Isolated initiation
- Isolated growth
- Coalescence
- Large crack growth

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