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The Growth of Fatigue Cracks in Eutectic Solders

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Abstract The grain size effect on grain boundary cracking in Pb-Sn eutectic during isothermal fatigue was investigated. Fatigue experiments were confined to two conditions : (1) 0.4% total strain range(approximately 0.2% plastic strain range), 1.67×10^{-3}/s frequency ; and (2) 1.5% total strain rante(approximately 1.2% plastic strain range), 8.33×10^{4}/s frequency. Fatigue specimens were cross-sectioned to monitor the depth of crack growth continuously and then, the maximum crack depths in units of the number of boundaries were plotted as functions of number of cycles for these two different strain ranges. The results revealed that the rate of crack growth(per cycle at fixed rate of crosshead motion) can be expressed as $dc/dN = (\Delta\varepsilon_P)^n c$ where n is typically 2, c is the crack length, $\Delta\varepsilon_P$ is the plastic strain range, and A is a "constant" that depends on whether the crack is deeper or shallower than its first triple point of the grain boundary. A decreases by about a factor of three after the crack hits the first triple point, indecating that the fatigue crack is trapped at the triple point of the grain boundaries.

INTRODUCTION

The dual-in-line package in which is solder-attatched into holes in the printed wiring board was a traditional method in microelectronic assembly technology. However, the advent of VLSI devices has gradually replaced it with surface mount technology because of its complexity and density problem. This surface mounted technology(paticularly, the leadless ceramic chip carrier) is widely utilized in the automotive industry as well as many of electronic goods such as computers, televisions, washing machines and so on. As a result, since the solder joint of the ceramic carrier must remain reliable for warrenty periods, its reliability has been a critical issue in determining the quality of the electrical connection between the chip and the printed circuit board undergo cyclic loading due to thermally-induced displacements[1~5]. Our previous reports also proved that intergranular fatigue cracks grow in eutectic solder joints during cyclic loading[6~9]. Such reports suggested that the fatigue life of solder joints subjected to thermal cycling is influenced by their grain size. In order to ensure the quality of electronic goods, it is necessary to predict the reliability of the solder joint associated with the microstructural evolution.

Typical strain ranges relevant to solder joint fatigue(where the surface mounted component undergoes in the automotive) fall anywhere between a small fraction of 1% strain to more than 10% strain. Under this range of conditions, fatigue life will typically fall any where between a few tens or hundreds of cycles to 10^4 or 10^5 cycles. Consequently, reliability of solder joints falls under the subject of low cycle fatigue. Fatigue with failure life up to 10^4 cycles is usually known as high strain or low cycle fatigue[10], and is described in ductile materials by the Coffin-Manson law. According to this law, the number of cycles to failure is inversely proportional to a power(approximately 2) of strain range. However, eutectic solder subjected to isothermal fatigue undergoes creep deformation because of its low melting point and it has been found that the crack growth interacts with the grain boundaries[11]. Such experimental observations motivated an investi-

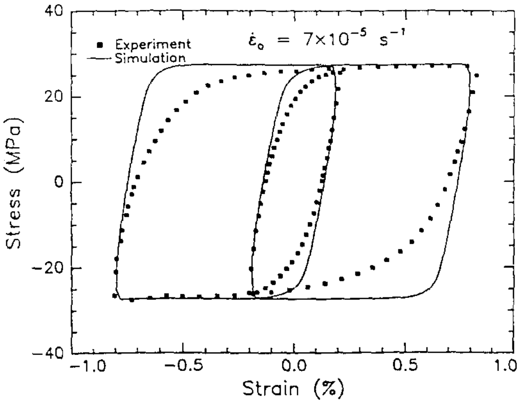


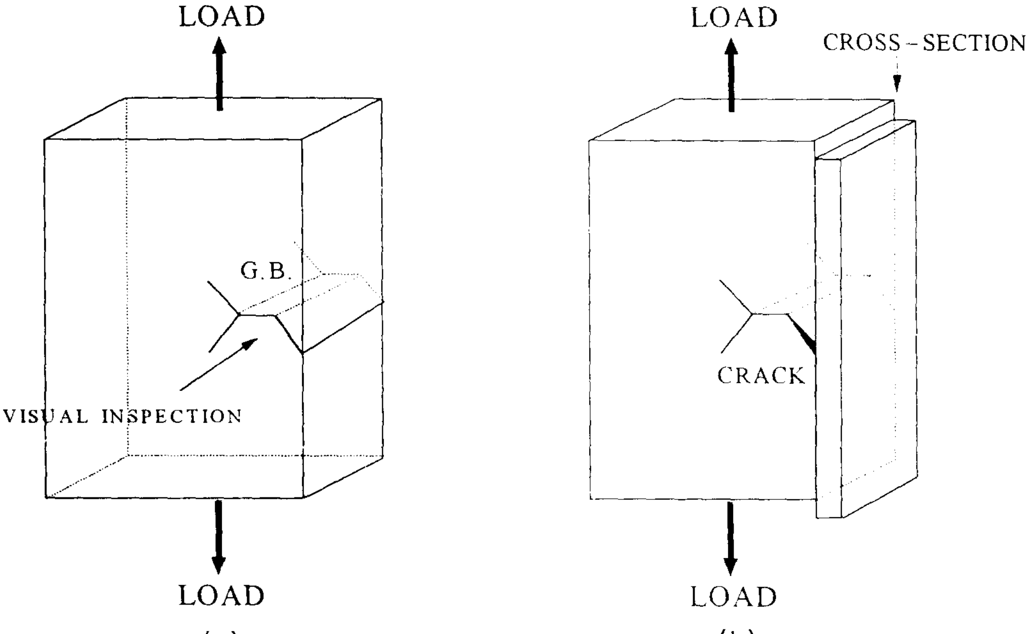
Fig. 1. Stress-strain data in tension-compression fatigue ; the simulation was obtained from the Wilcox PhD thesis[14].

gation of whether the resulting crack growth law in eutectic solders is consistent with the Coffin-Manson law in which the fatigue life is determined by strain range without the effect of the microstructural evolution.

EXPERIMENTS

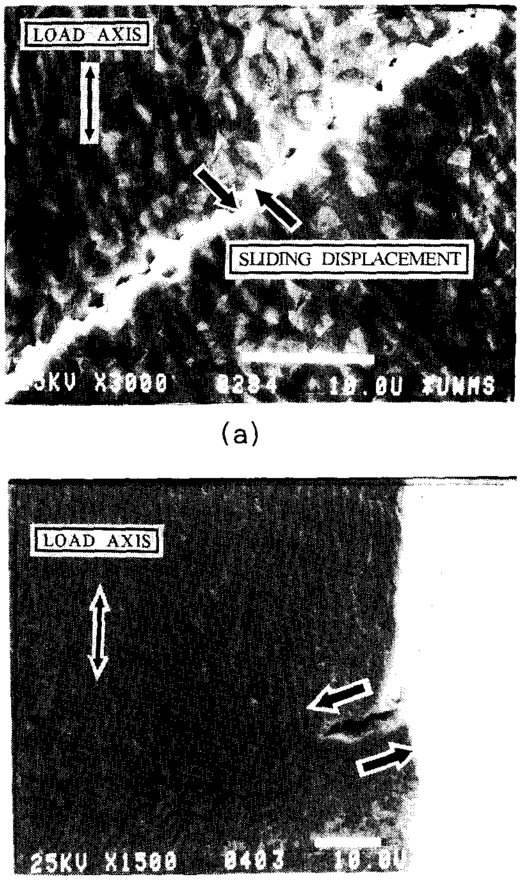
Ingots of Pb-Sn eutectic with 99.99% purity were cast in dog bone-shaped Al molds. Gage sections of fatigue specimens were 3.0mm thick, 10mm wide, and 7.5mm long. All of the fatigue specimens studied had an equiaxed grain structure, whose grain size were 250–300㎛. A special method was adopted to obtain a type of specimen consisting of an equiaxed grain structure[11].

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. Stress-strain data obtained from tension-compression fatigue are shown in Figure 1, indicating that strain range was approximately 1.5%. The simulation data were estimated from the setting value of 0.002inch/minute for the crosshead speeds in the Instron. A symmetric, triangular waveform was utilized. During the test, load and strain was monitored continuously. Strain was estimated by using linear



(a) (b)

Fig. 2. The schematic drawing of fatigue specimen suvjected to the cyclic loading ; a) observation of cracked grain boundaries in situ & b)cross-sectioning of cracked grain boundaries.



(a)

(b)

Fig. 3. Scanning Electron Micrographs showing a) Sliding displacement b) initiation of a intergranular crack.

voltage differential transformers. A 500 pound load cell was used to monitor load. Time, load, and displacement were recorded with a personal computer-based data acquisition system employing 5-1/2 digit Keithley voltmeters through as IEEE interface.

The maximum crack depths in units of the number of grain boundaries were measured by successive cross-sectioning fatigue specimens at a regular interval of 20μm. A microtome was adopted as means of obtaining metallographic cross-sections as the following ; a reference mark was first introduced into the surface of the fatigue specimen by utilizing the microtome and then, the distance from a cracked grain boundary to the fiducial mark was measured to determine the orientation of the cracked grain boundary with respect to the stress direction as shown in Figure 2. This figure indicates that the cross-sectional direction is parallel to the stress axis. The resulting crack depth was obtained from the cracked boundary orientation and the crack length observed on the surface under the SEM[11]. The measurement technique of the crack depth shown above might be first tried in the world.

RESULTS AND DISCUSSION

Although there are fundamental differences in rate-controlling mechanisms between high temperature deformation(creep) and low temperature plasticity, plasticity is not ordinarily relevant to the deformation of the Pb-Sn eutectic because of its low melting point. Since room temperature is about 2/3 the melting point of the eutectic and so, its fatigue failure is caused by the creep-fatigue interaction. Indeed, it has been already shown in our earlier reports[5, 9] that intergranular failure resulting from creep deformation takes place under a certain test condition of temperature, stress, strain range and frequency in eutectic solder(i. e. a strain rate below 10^{-4}/s). Furthermore, it has been also reported that such a failure is associated with the sliding properties of the grain boundary under the cyclic loading. Since grain boundary sliding resulting from the creep-fatigue interaction can cause various types of intergranular damage such as cavitation, internal wedge cracking, environmental damage, and so on, the means of intergranular crack nucleation is open to dispute. The vidual inspection shows in this work that the sliding displacement first appears as uniform contrast across the entire length of a grain boundary as shown in Figure 3a, resulting in the initiation of intergranular cracking at the surface as shown in Figure 3b and Figure 4.

A close exmination of surface crack propagation in situ·shows that once a crack initiates along a grain boundary, it does not grow continuously for a certain period of time and then,

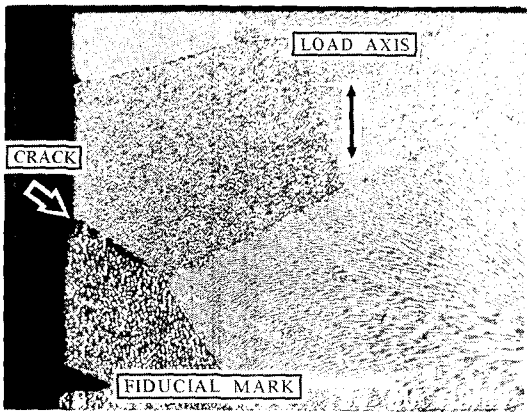
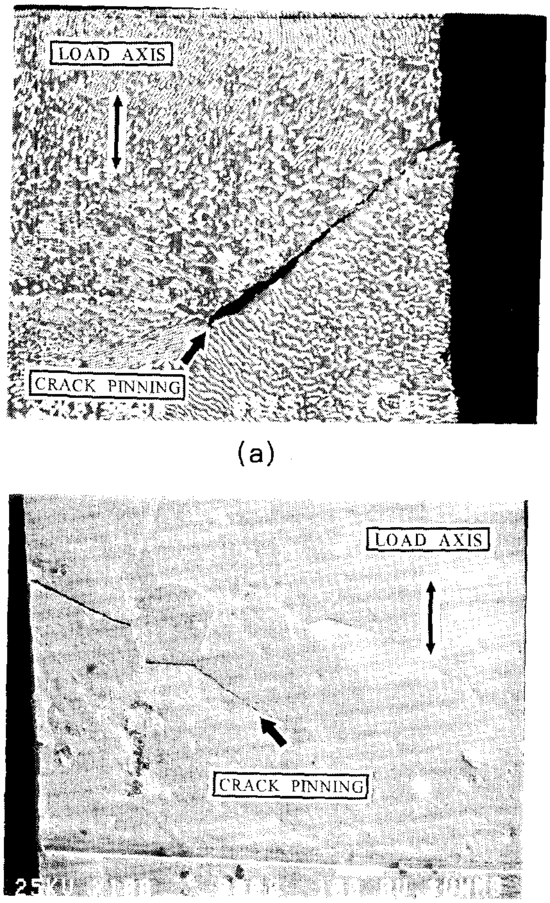


Fig. 4. A SEM(BEI) showing the propagation of a intergranular crack inward the specimen.



(a)

(b)

Fig. 5. Scanning electron micrographs showing the pinning of the crack tip at the triple point of grain boundaries ; a) pinning at 1 triple point & b) crack growth aspect in a discrete manner.

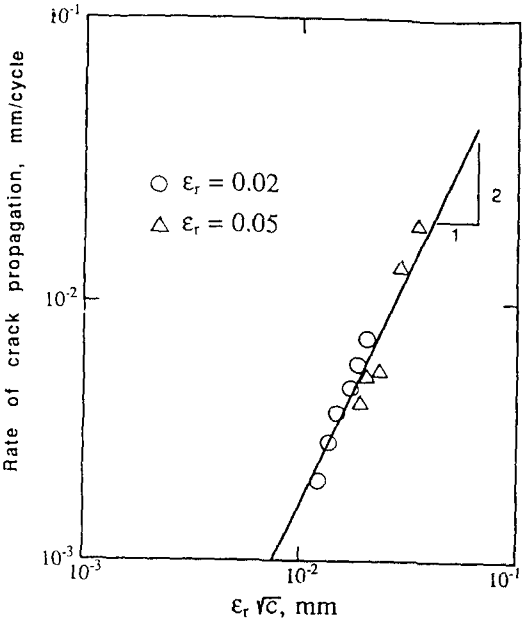


Fig. 6. The fatigue crack growth rate for OFHC copper [after Boettner 1965].

propagate suddenly onto adjacent grain boundary. The resulting aspect of the crack propagation observed on the specimen surface was a discontinuous motion due to its pinning at the triple point of the grain boundries as shown in Figure 5. Particularly, this work proves through the special cross-sectioning technique using the microtome that such an intergranular crack initiated at the specimen surface tends to propagate inward the specimen without any internal damage. These experimental observations, which the surface crack growth can be influenced by the microstructural evolution, motivated to identify whether the resulting crack growth aspect inward the specimen is consistent with the Coffin-Manson law.

The effect of grain size on the rate of crack growth

It has been known that the growth rate can be expressed semiempirically as[12] :

$$\frac{dC}{dN} \propto (\Delta K)^{b} \qquad (1)$$

where ΔK indicates the range of applied(nominal) stress intensity factor, c is the crack

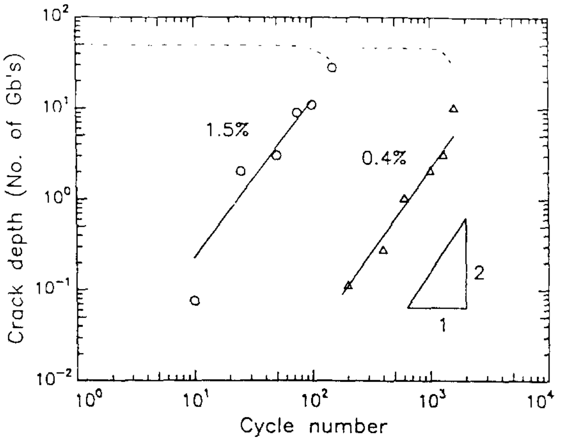


Fig. 7. The set of experimental data representing the maximum crack depths as a function of the number of cycle for two different strain ranges ; logC 〈1 indicates that a crack grows less than 1 triple point deep.

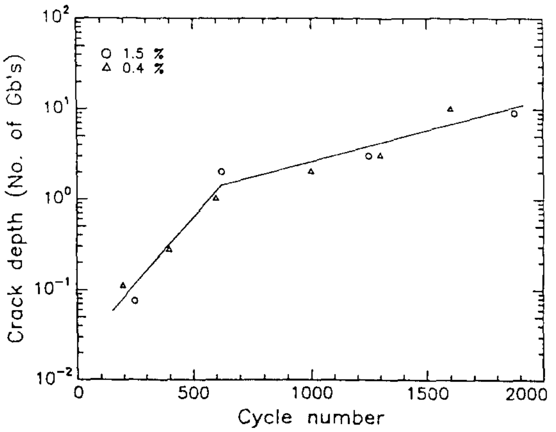


Fig. 8. A semilog plot showing the crack depths as a function of the number of cycles. The data of the 1.5% strain range have been multiplied along the abscissa by 25 so that they overlap the data at the 0.4%.

length and b is typically 4. This equation is often called Paris' law. The effect of strain on crack propagation has also been reported as shown in Figure 6[13].

The empirical expression relates growth to the imposed strain range :

$$\frac{dC}{dN} \propto \Delta\varepsilon(\sqrt{\pi c})^{p} \qquad (2)$$

where $\Delta\varepsilon$ is the total strain range and p is a 2–5[13]. Since the applied nominal stress intensity factor is related to the strain range as $\Delta\varepsilon = \Delta\sigma^m$ where m is about 2[13], above two equations seem to be consistent.

In the present work, since a crack was generated due to grain boundary sliding at the surface of fatigue specimens as shown in previous figures, it was deemed unsuitable to use the average crack length as a measure of cracking, but rather the maximum crack depth in units of the number of boundaries(i.e. the crack depth normalized by the grain size). Maximum crack depths are plotted, on a log–log scales in Figure 7, as functions of number of cycles for 0.4% and 1.5% strain ranges. The data can be fit adequately well with lines of slope 2, although above crack depths of 10 grain boundaries the data become suspect because of specimen size effects as evidenced in a drop in stress range drop by about 10%. consequently, plotted like this, the data suggest the following crack growth law based on plastic strain range :

$$\frac{d\log\sqrt{C}}{d\log N} \propto (\Delta\varepsilon_p)^n \qquad (3)$$

where n is constant and $\Delta\varepsilon_p$ is the plastic strain range. The equation (3) is consistent with the Coffin–Manson law in a point of view that the crack growth rate to determine the fatigue life can be expressed as a function of the plastic strain range. The data can also be presented in a more conventional, semilog plot, Figure 8.

As a measure of whether the cracks are becoming large enough that specimen size effects become important, in figure 8, the data of the 1.5% strain range have been multiplied along the abscissa by 25 so that they overlap the data at 0.4% strain. It is seen, therefore, that to within that scatter in the data, the two sets of experimental data have the same shape apart from a scaling factor in the number of cycles. Both sets of data, when plotted in this form, demonstrate a knee when the crack becomes 1 grain boundary deep. The data suggest the following crack growth laws :

$$\frac{d\log C}{dN} \propto A(\Delta\varepsilon_P)^n \qquad (4)$$

and

$$\frac{dC}{dN} = \alpha AC(\Delta\varepsilon_P)^n \qquad (5)$$

where $\alpha = 1$ for cracks that have not reached the first triple point and $\alpha = 1/3$ for cracks that have penetrated further than one triple point deep. Here, the multiplicative factor α is, to within the scatter of the data, independent of strain range, and estimated from the slope of the set of experimental data shwon in Figure 8.

Now, consider the significance of the crack growth laws in equation (5). The present result introduces an important point regarding the efficacy of using the microtome as means of obtaining metallographic cross-sections to understand the effect of the microstructural evolution on the crack growth rate. That is, although previous articles have reported that the crack growth rate is influenced by the grain size, they did not prove it through the visual inspection. On the other hand, it is clearly shown in this work that there should be a transition in growth rate when a crack reaches 1 triple point deep, suggesting the jerky behavior of crack growth. One implication of the present result would be to use the solder joint with a grain shape elongated parallel to the outside surface of the solder fillet(i.e. stress axis) to enhance the reliability of electronic goods.

SUMMARY

The present work indicates that in eutectic solders prolonged cyclic loading results in continuous sliding of the grain bondaries until the intergranular cracks initiate at the specimen surface. Through the microstructural analysis, it was investigated that such a surface crack, which appears as uniform contrast along the entire length of a grain boundary as a result of its sliding(Figure 3a), grows in the discrete manner(i.e. discontinuous propagation).

The cross-sectioning of fatigue cracked-specimens was performed to identify whether the rate of the crack growth into the center of the specimen is also influenced by the grain size effect(i.e. there exists a change in growth rate when a crack reaches 1 triple point deep). Then, it was found that the best description for crack growth at constant strain rate is $dc/dN = \alpha AC(\Delta\varepsilon_P)^n$ where α decreases by about a factor of 3(α ; 1 → 1/3) when the crack grows larger than 1 triple point deep. Such an abrupt reduction in the crack growth rate manifests that the fatigue crack inward dose not grow continuously onto adjacent grain boundary but wait for a certain period of time due to its pinning at the triple point of the grain boundaries in a same way that the surface crack propagates.

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