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Cavitation and cracking in as-cast and superplastic Pb–Sn eutectic during high-temperature fatigue

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A variety of solder joints, particular in the computer/electronics industry are subject to mechanical and thermal fatigue. Although extensive data have been published on solder joint lifetimes under various fatigue loading conditions, very limited information is available on the microstructural features that contribute to failure. We have examined the behaviour of Pb–Sn eutectic solder under fatigue deformation, with particular focus on cracking in both as-cast and recrystallized materials, as these microstructures may be present in solder interconnections.

Since the early work of Pearson [1] almost fifty years ago, the monotonic deformation behaviour of Pb–Sn eutectic alloy has been the subject of numerous investigations [2–5]. These have, in large part, been prompted by the observation of superplasticity in the fine-grained, equiaxed material, in which extensions of a few thousand per cent strain before fracture and nearly 100% reduction in area, are observed. Although cavitation appears to be a common failure mechanism in a number of other superplastic materials [6, 7], there are to date no reports of cavitation or cracking in the Pb–Sn system. For example, Humphries and Ridley [8] showed no detectable increase in the density of voids in specimens strained to 300%. Certain single-phase materials, such as high-purity aluminium, also do not exhibit cavitation when tested in the creep regime [9].

In contrast to the lack of cavitation in high-purity aluminium tested under creep conditions, cavitation has been demonstrated in aluminium tested in fatigue. In the early work of Blucher and Grant [10], large cavities were observed in high-purity aluminium, tested to failure in axial fatigue. Yavari and Langdon [11] have shown cavitation in 99.99% aluminium under reverse bending fatigue. This suggests that materials which do not show cavitation or cracking when tested in uniaxial creep may be prone to cavitation when tested in fatigue. The superplastic Pb–Sn alloy system, which does not cavitate when tested in uniaxial tension, therefore, lends itself as a suitable material to check this possibility. Tests were performed in reverse-bend fatigue to identify cavitation in this material. Specimens were tested in the as-cast and in the rolled/recrystallized (superplastic) condition. Details of the uniaxial and cyclic deformation behaviour of as-cast and superplastic Pb–Sn alloy will be presented elsewhere [12].

Reverse-bending fatigue tests were conducted on as-cast and superplastic Pb–Sn specimens having the following impurities, (wt p.p.m.) Si 30, Zn < 100, Mn < 3 and Fe 10. Specimens with a tapered profile were machined from as-cast bars, having dimensions 20 mm × 15 mm × 300 mm. The superplastic Pb–Sn specimens were machined from a 3 mm sheet. All specimens were initially etched deeply to remove the disturbed surface layer. Samples were polished using 1 μm diamond paste; final polishing was carried out using 0.3 μm alumina powder. Both as-cast and superplastic specimens were electropolished in a solution consisting of sodium acetate, acetic acid and water at 40 V using a platinum cathode [13]. Prior to testing, samples were examined in an optical and a scanning electron microscope and detailed examination revealed no evidence for cavities or cracks in the pretest condition. The as-cast material had an initial mean lamellar spacing of 3.7 μm and a lamellar colony (grain) size of 50 to 80 μm, while the rolled/recrystallized (superplastic) material had a starting grain size of 5.8 μm.

Specimens were tested in air at room temperature, equivalent to 0.65 T_e, where T_e is the eutectic temperature. The testing machine is a modified form of the equipment employed by Yavari and Langdon [14]. Tests were conducted at a frequency of 5.5×10^{-3} Hz and a strain amplitude of $\pm 0.5\%$. Tests were terminated at zero strain amplitude after a predetermined number of cycles, recorded on a mechanical counter.

Tests were conducted specifically to detect the point at which cavities or cracks were formed. In these experiments, testing was interrupted at 100 cycle intervals up to 400 cycles, and at 400 cycle intervals thereafter. The sample surfaces were examined in the optical and scanning microscope at each stage in the testing. The as-cast microstructure, consisting of a lamellar distribution of the phases, was retained with no evidence for the formation of cavities or cracks up to 1200 cycles. Further testing to 1600 cycles resulted in the development of both cavities and cracks at the majority of the boundaries separating the lamellar colonies (Fig. 1). The morphology of the cracks is visible in Fig. 1b along the boundary marked AB. The cracks were largely isolated at this stage in the deformation, although linkage to form larger cracks was observed in a few locations. Decohesion at the lead-rich/tin-rich lamellar phase boundaries was not observed.

Fig. 2 shows scanning electron micrographs from the Pb–Sn superplastic alloy tested to 1600 cycles. Here, decohesion is observed at the Pb–Sn interphase boundaries along with the formation of small cavities ($\sim 1\,\mu$m) at somee of the boundaries (Fig. 2b). This type of cracking and cavitation is absent at the Pb–Pb

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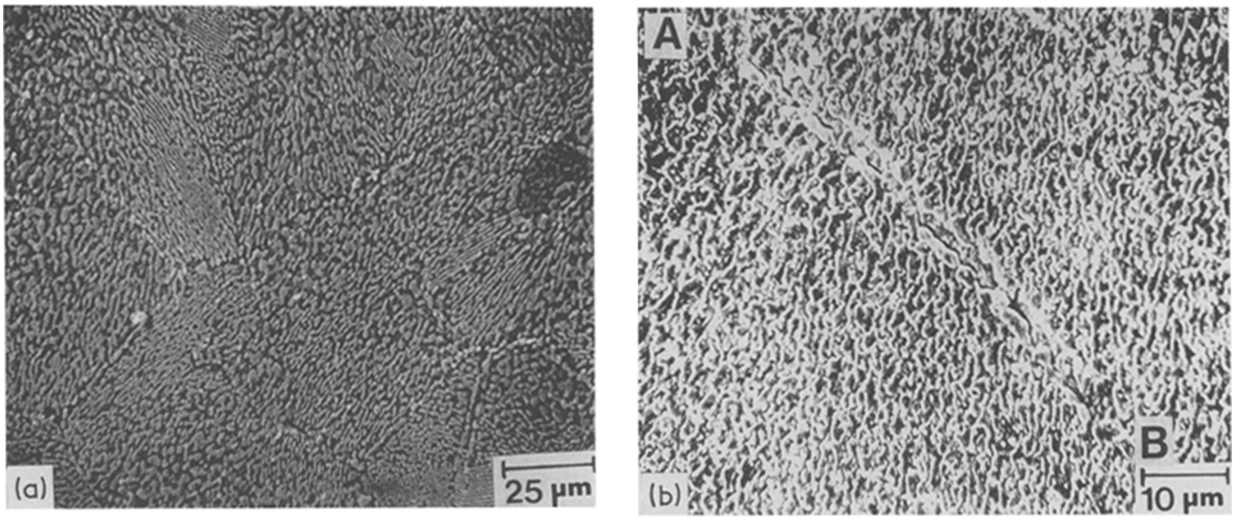

Figure 1 Observations of cracking at intercolony boundaries in as-cast Pb–Sn eutectic tested to 1600 cycles at room temperature. Test frequency, 5.5×10^{-3} Hz; strain amplitude of testing, ±0.5%.

and Sn–Sn grain boundaries. It has been observed in earlier studies of cavitation that the different types of boundaries are not equally susceptible to cavity and crack formation. In the case of the Pb–Sn superplastic alloy, it was shown from uniaxial tensile tests that the largest sliding displacements occur at the Sn–Sn intercrystalline boundaries while the Pb–Sn interphase boundaries undergo intermediate levels of sliding [15]. The role of sliding at the different types of interfaces and their influence on cavitation in fatigue has not been reported; i.e. the cracking at the α/β interface has not been linked to the sliding characteristics at this interface. The present results do warrant comparison with the results obtained on cavitation in an aluminium bronze alloy, where the incidence of cavitation at the different interfaces was studied in uniaxial tension [16]. It was noted that the distribution of cavitation was five times as large at the α/β interface compared to that at the α/α interface and 15 times as much as that at the β/β interface. Similar conclusions have been reached in two other materials tested at high temperatures [17, 18].

The present results show that cavities and cracks are formed in the as-cast and superplastic Pb–Sn alloy tested in fatigue at room temperature. With the exception of a study showing cavitation in this alloy at high strain rates [19], there are no reports of cavitation in this alloy tested in tension. Given the similar observations for aluminium [10, 11], it may be that this is a general phenomenon; cyclic deformation leads to cavitation and cracking in materials that do not normally form cavities in uniaxial creep.

We will briefly mention some of the factors that enhance cavitation during high-temperature fatigue in comparison to that in uniaxial creep. Cavitation and failure at high temperatures are closely linked with the processes of grain-boundary migration, sliding and diffusion. It is usually assumed that high-stress concentrations develop at sliding grain boundaries, at grain-boundary triple junctions or other points of highly localized plastic deformation. In a HVEM study of the development of voids in fatigued copper, Page and Weertman [20] concluded that the grain-boundary voids produced by creep deformation are nucleated at a rate that was lower than the corresponding rate in fatigue. The nucleation of voids in

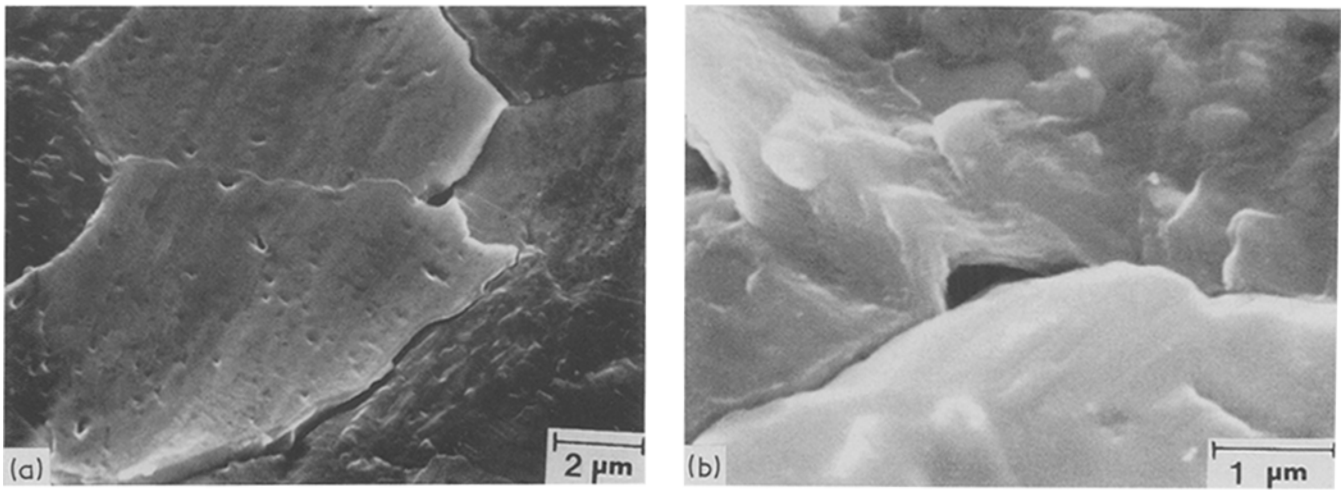

Figure 2 Cavitation and cracking at the Pb/Sn interphase boundaries in superplastic Pb–Sn alloy fatigue tested at room temperature. Test frequency, 5.5×10^{-3} Hz; strain amplitude of testing, ±0.5%; number of cycles, 1600.

fatigue occurred at the peaks of coarse and fine serrations which have an associated high stress concentration. The development of a serrated profile of the boundaries is facilitated by the ease with which boundaries can migrate and slide during deformation. Although there are no experimental reports demonstrating migration and sliding in the materials investigated in this study, it is known that extensive boundary migration, sliding, and serrated morphologies of the boundaries are observed in materials such as lead, Pb-2% Sn and aluminium when subjected to cyclic deformation at high temperatures [21–23]. An additional conclusion based on qualitative observation in pure aluminium, after fatigue testing at high temperatures, is that the maximum amounts of sliding tend to occur at boundaries where the amounts of migration are small [24, 25]. Because for the two-phase Pb–Sn system, the α/β boundaries do not migrate, this strain-relieving process is not available and may account for the enhanced cracking at these interfaces. An alternate view to explain the higher cavitation rates observed in fatigue is that a higher excess vacancy concentration is generated during fatigue deformation compared to creep, and that void nucleation and growth are facilitated by the excess vacancies [26].

In conclusion: (1) cyclic deformation at room temperature results in the development of cavities and cracks in as-cast and superplastic eutectic Pb–Sn alloy; and (2) cavitation and cracking takes place at the boundaries separating adjacent lamellar colonies in the as-cast eutectic and at the interphase boundaries in fine-grained, equiaxed, superplastic material.

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