Research note

On the failure path in shear-tested solder joints

W.H. Moy, Y.-L. Shen *

Department of Mechanical Engineering, University of New Mexico, Albuquerque, NM 87131, USA

Received 27 February 2006; received in revised form 26 April 2006
Available online 9 October 2006

Abstract

Failure of solder joints under shear frequently occurs along a path near and parallel to, but not necessarily exactly at, the interface between the alloy and the bonding material. A numerical finite element analysis was employed to simulate the deformation in solder during cyclic lap-shear testing. High magnitudes of equivalent plastic strain were seen to initiate from the corner regions and spread into the solder along a concentrated band close to the interface. Damage can be expected to occur along the localized band, thus rationalizing the experimentally observed failure path. The effect of solder geometry was also explored in this study.

© 2006 Elsevier Ltd. All rights reserved.

1. Introduction

Failure of solder joints has been a serious reliability problem in microelectronic packages. The formation of cracks in solder is a consequence of creep and/or fatigue, coupled with the possible microstructural change during the deformation history. One commonly observed failure pattern in real-life and laboratory shear-tested solder joints is that cracking appears close to, but not at, the interface between the solder alloy and the bonding material [1–7]. This includes both the traditional tin (Sn)-lead (Pb) solder and many Sn-based Pb-free solder materials. An example is shown in Fig. 1, where the dominant failure path in the Sn–Pb solder is near the interface with the copper (Cu) substrate. Note fracture is entirely within solder, outside of the thin intermetallic layer (barely discernible in the figures) between the solder and Cu. Of course, there are also experimental observations of solder joint failure exactly at the interface or even inside the intermetallic (e.g., [8,9]), which may be explained by the weak interfacial strength or brittle nature of the intermetallic etc. under the particular loading conditions. However, it is the case of near-interface fracture within the solder that is in need of a mechanistic clarification.

Satisfactory explanations for this type of near-interface failure path have not been available to date. Although microstructural details (such as fracture along grain boundaries or phase boundaries) can certainly influence the path, there is a lack of understanding on why failure frequently takes place near (not at, nor well away from) the interface. In this work we seek to provide a rationale by carrying out numerical finite element analyses of the solder lap-shear testing. We show that, even without microscopic influences, the evolution of equivalent plastic strain can be correlated with this type of unique tendency in the solder joint.

2. Model

The computational model is shown in Fig. 2, with the solder joint bonded to two copper blocks (substrates). In the simulation horizontal displacements (Δl in the x-direction) were imposed at the far right end of the lower Cu block. The x-direction movement of the far left edge of the upper Cu is forbidden, but movement in the y-direction is allowed except that the lower-left corner of the upper copper is totally fixed. The nominal shear strain in the solder is defined to be Δl/h. The relative thicknesses of solder and substrate were chosen such that apparent bending resulting from the loading is kept at minimum. The solder joint itself was discretized into 1200 four-noded linear...
elements. Preliminary calculations have demonstrated mesh convergence at this fine element size. Each Cu substrate was discretized into 3200 four-noded linear elements. The calculations were based on the plane strain condition, which effectively simulates the nominal simple shearing mode of the solder [10]. (We have also conducted simulations under the plane stress condition, and the same qualitative conclusions were reached. These plane stress results are therefore not presented.) The thin intermetallic layer at the solder/substrate interface is not included in most of the calculations presented in this article. As long as the intermetallic thickness is much smaller than the solder thickness, the stress and strain states in solder will be affected only very slightly (see discussion below). In the model, Cu is taken to be isotropic linear elastic, with a Young’s modulus of 114 GPa and a Poisson’s ratio of 0.31. The solder is taken to be isotropic elastic–plastic with initial strain hardening, following von Mises plasticity. Its input stress–strain response was based on the experimental room-temperature tensile behavior of bulk Sn-3.5 Ag specimens air-cooled from 240 °C [11]. The Young’s modulus and Poisson’s ratio of the solder are 48 GPa and 0.36, respectively, and the elastic limit is 21.5 MPa. The strain hardening response follows the experimental curve up to 32.3 MPa at a plastic strain of 0.16, beyond which the material is assumed to be perfectly plastic [10]. Note that we do not take the time-dependent deformation of solder into account; using rate-independent plasticity facilitates a straightforward evaluation of mechanical features, which is the primary objective of this work. The finite element program ABAQUS [12] was employed in the calculations. In the presentation that follows, the solder geometry is specified by its aspect ratio (”h/w,” Fig. 2).

3. Results and discussion

Here we present contour plots of equivalent plastic strain in the solder joints with various geometries and deformation histories. Within the continuum mechanics framework, the equivalent plastic strain, representing the accumulation of irrecoverable deformation in an elastic–plastic solid, is a parameter directly related to the propensity of damage initiation (e.g., formation of microvoids or microcracks in ductile solids). Fig. 3 shows the evolution of equivalent plastic strain for the solder geometry of 0.25/1.27 (h = 0.25 mm and w = 1.27 mm) during cyclic shearing, with a nominal shear strain range between 0% and 5%. In Fig. 3(a) the solder is at the end of the first one-half cycle (peak strain), and in Fig. 3(b) and (c) the solder is at the end of the first full cycle and ten full cycles, respectively. For clarity purpose only parts of the Cu substrates close to the joint are included in the figures, and the plastic strain in Cu is zero since it is elastic. It is evident that the plastic deformation field in solder is highly non-uniform. In Fig. 3(a), strong plasticity appears in the four corner regions (having local shear strain concentration) and tends to propagate into the solder along approximately the 45° direction. However, the dominant deformation mode of the entire joint is horizontal shear, so linking of the plastic localization initiating from the two interface corners tends to occur, resulting in a band parallel to each interface.
There is no intense plasticity in the mid-thickness regions of the joint, because the material elements there have more freedom to experience rotation, rather than deformation, to help accommodate the applied shear. After one full cycle (Fig. 3(b)), a vague deformation band near each interface can be seen. At the end of the tenth loading cycle (Fig. 3(c)), the bands become distinct with very high plastic strain values within. Note the deformation bands are close to, but not at, the interface between solder and the substrates, which is consistent with the dominant failure path in many actual tests.

We have also examined the various stress and strain components in detail, and observed that strong plasticity is associated with a dominant shear that is highly non-uniform in the joint as long as the solder width is finite (or the aspect ratio is not too close to zero). Even if the substrate material is treated as a non-deformable rigid solid, the plastic band in solder still exists. We now present the equiv-
alent plastic strain contour plots for the cases with different solder geometries (two with a smaller aspect ratio and one with a greater aspect ratio). Fig. 4(a) and (b) shows the results for the 0.25/6.35 solder at the end of the first and tenth cycles, respectively. The corresponding plots for the 0.5/6.35 solder are shown in Fig. 5(a) and (b) and those for the 0.5/1.27 solder are shown in Fig. 6(a) and (b). (Note that the four solder geometries considered in this paper have an increasing aspect ratio in the order of Figs. 4, 5, 3, 6.) It can be seen from Fig. 4(a) and (b) that there is no discrete plastic deformation band when the solder aspect ratio is very small. In Fig. 4(a), relatively strong plasticity occurs only in two of the four corners. From a previous study of shear transfer in solder joints, the buildup of shear strain in solder was found to be very ineffective when its aspect ratio is low [10]. Here it is observed that strong plasticity at corners first tends to propagate along the near 45° direction, but for this low-aspect-ratio solder, the rotational freedom in the mid-thickness part of the joint is suppressed due apparently to the longer interfaces relative to the thickness dimension. This prevents the near-interface bands from forming, even at the end of ten loading cycles (Fig. 4(b)). Fig. 5(a) and (b) may be viewed as a “transition” case between low and sufficiently high aspect ratios. Discernible deformation bands somewhat parallel to the interface can be seen. Parts of the bands appear right at the interface but others are a small distance away. Compared to the case of Fig. 4(a) and (b), the strain magnitudes in Fig. 5(a) and (b) are much greater, indicating a more effective transmission of deformation from the substrates to the joint, under the same nominal shear strain.

Fig. 6(a) and (b) represent the case of highest aspect ratio presented in this paper. As in the case of Fig. 3 shown previously, the deformation bands already exist after one loading cycle and become very well defined after ten cycles. Except at the four corner regions, the bands are near but not at the interface. It may be predicted that, with further deformation, failure initiation will occur at locations along the strong plastic bands. The exact cracking feature may depend on the local microstructure, but the macroscopic failure path is largely limited by the well developed plastic band parallel to the interface. The coalescence of local damage can lead to a major crack which eventually severs the joint.

Although the models shown above do not include the intermetallic layers, we have performed simulations with the “flat” and “nodular” type of intermetallic between the copper substrate and the solder. We observed that the deformation pattern in solder is essentially the same as in

Fig. 4. Contours of equivalent plastic strain evolved in solder of the geometry 0.25/6.35. In (a) the solder is at the end of the first cycle, with the nominal shear strain history 0 → 5% → 0. In (b) the solder is at the end of the 10 cycles between the nominal strains of 0% and 5%. Only a portion of the copper substrates is included in the plots.
the cases without the intermetallic. A representative result is shown in Fig. 7. Fig. 7(a) shows the contour plot of von Mises effective stress in the solder and the thin intermetallic layers (Cu$_6$Sn$_5$) sandwiching the solder. Higher stress magnitudes following the intermetallic morphology can be observed. The equivalent plastic strain contour plot is

Fig. 5. Contours of equivalent plastic strain evolved in solder of the geometry 0.5/6.35. In (a) the solder is at the end of the first cycle, with the nominal shear strain history $0 \rightarrow 5\% \rightarrow 0$. In (b) the solder is at the end of the 10 cycles between the nominal strains of 0% and 5%. Only a portion of the copper substrates is included in the plots.

Fig. 6. Contours of equivalent plastic strain evolved in solder of the geometry 0.5/1.27. In (a) the solder is at the end of the first cycle, with the nominal shear strain history $0 \rightarrow 5\% \rightarrow 0$. In (b) the solder is at the end of the 10 cycles between the nominal strains of 0% and 5%. Only a portion of the copper substrates is included in the plots.
shown in Fig. 7(b), with the overall pattern very similar to those in cases without the intermetallic. The presence of intermetallic simply served to reduce the solder thickness and all deformation features in solder displayed in the above figures were still in place. Another simplification we made in the present modeling, as mentioned previously, is the exclusion of time-dependent material properties for solder. We have also conducted the same type of analysis with the viscoplastic behavior of solder incorporated. The results illustrated that, as the shear rate increases, the concentrated plastic band tends to become more diffused due to the strain rate hardening effect. The fundamental feature (strong plastic band closely parallel to, but not at, the interface), however, still remained.

4. Conclusions

In summary, we have carried out finite element analyses of lap-shear testing of solder joints during cyclic deformation. The primary objective is to offer a mechanistic basis on why the dominant failure path in the sheared solder is frequently inside the solder alloy a short distance away from the interface between solder and the bonding material. The numerically simulated plastic strain field reveals that plastic deformation in the joint is highly non-uniform. Except for solder joints with very low aspect ratios, a band of strong plasticity develops near each interface over the deformation history, leading to a preferred damage initiation path.

References