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Microstructural Changes in Eutectic Tin–Lead Alloy due to Severe Bending*

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Abstract

Severe plastic deformation in an eutectic tin–lead alloy is studied by imposing fast bending at room temperature, in an attempt to examine the microstructural response in the absence of thermally activated diffusion processes. A change in microstructure due to this purely mechanically imposed load is observed: the tin-rich matrix phase appears to be extruded out of the narrow region between neighboring layers of the lead-rich phase and alterations in the colony structure occur. A micromechanism is proposed to rationalize the experimental observations.

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1. Introduction

Tin (Sn)–lead (Pb) alloys with near eutectic compositions are widely used as soldering materials in the packaging of microelectronic devices. However, their long-term structural reliability has always been a major concern [1-3]. One of the reliability problems is thermomechanical fatigue [4-11]. Mechanical stresses in solders are generated due to thermal expansion/contraction differences of the components they connect, as a consequence of temperature fluctuations stemming from the operation environment. Material degradation is caused not only by cyclic deformation, but also by creep damage because of the inherent low melting point such that even room temperature is sufficient to trigger high temperature deformation mechanisms. These are further compounded by the fact that the alloy microstructure changes with time, even at room temperature, with or without the presence of stresses. Therefore, damage in Sn–Pb solder inevitably involves both mechanically induced mechanisms and atomic diffusion, the latter of which can lead to microstructural changes. Although the interplay of mechanical and diffusional effects plays a crucial role, attempting to construct a thorough picture of the problem calls for a fundamental understanding of the individual processes. While the diffusion phenomenon can be studied by employing a variety of techniques without applied stresses [12-15], the pure mechanical effect, however, demands experiments featuring large mechanical deformation for a short duration (to avoid atomic diffusion processes). In the present work, we studied the mechanical effect by applying severe bending to quickly achieve large-scale deformation in a straightforward manner. In particular, we report in this communication that a change in phase morphology occurs in the eutectic Sn–Pb alloy, even under this pure mechanical action at room temperature.

2. Experimental

The as-received eutectic Sn–Pb alloy was in the form of extruded bars retrieved from prolonged storage. In the as-received state, large "islands" of Pb-rich phase embedded within the Sn-rich matrix were observed microscopically. Re-melting was conducted by heating the material (placed inside an alumina crucible) to 232°C for 40 minutes in an air furnace to allow complete melting. No environmental control was imposed. Solidification took place by letting the samples, approximately 8 mm × 8 mm × 80 mm in dimension, cool to room temperature in ambient air. The bending was carried out using a typical vise operated by hand, in which the loading forced the sample into a horseshoe shape, as schematically

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shown in Fig. 1. No detectable cracking exists after bending. The deformed piece was then sectioned along the most severely deformed part (along AB in Fig. 1) for metallography examinations.

Conventional optical microscopy was employed to examine the evolution of microstructure. Following polishing with diamond paste up to the level of 0.25 μm, the specimens were etched with a solution of one part acetic acid, one part nitric acid and four parts glycerol at room temperature for one to two minutes. The dual phase structure of the eutectic alloy was thus revealed.

3. Results and Discussion

Figures 2(a) and 2(b) show the micrographs of the as-solidified alloy at two different magnifications. A typical lamellar configuration, with layers of Pb-rich phase (dark) embedded within the Sn-rich matrix (light), is evident. The layers are oriented in roughly the same direction in each "colony". The colony structure can be discerned with a low magnification (Fig. 2(b)).

Figures 3(a) and 3(b) show the micrographs of a severely deformed specimen, at magnifications corresponding to those in Figs. 2(a) and 2(b), respectively. The images were taken on the center cross section, at a location near the concave (inner) side of the bent specimen (marked with a rectangle in Fig. 1). It is clear that the phase morphology has changed dramatically. Within the colony, the interspacing between neighboring Pb-rich layers becomes much smaller after bending, while the Pb-rich phase itself appears largely unaffected (Fig. 3(a)). Therefore, the relative volume fraction of the two phases within the colonies appears to be altered. It is noticed, however, that the Sn-rich phase becomes more abundant at the colony boundaries. This can also be seen by recognizing that a more distinct colony structure exists in Fig. 3(b) compared to that in Fig. 2(b), due to the enhanced and reduced Sn-rich background, respectively, at the colony boundaries and within the colonies after bending. A similar microscopic feature was found at locations near the convex (outer) side of the specimen.

The above observations suggest that, upon severe bending, the Sn-rich phase tends to be "extruded" from within the colonies to the colony boundaries. Since the entire deformation process was completed within several seconds and only a slight temperature rise was felt over this short duration, atomic diffusion is presumably not responsible for the microstructural change. Large-scale plastic flow should be the dominant mechanism. From a micromechanical standpoint, the Pb-rich and Sn-rich phases, like pure Pb and Sn, have comparable strength and flow behavior at room temperature [16]. As a consequence, neither of these two phases by nature would flow much more easily than the other. According to the micrographs, however, the size and shape of the individual Pb-rich layers remain largely unchanged, which is an indication that the confinement of the Pb-rich layers within the surrounding matrix greatly suppresses their flow capability. The overall deformation of the specimen is accomplished by the plastic flow of the Sn-rich matrix.

The reason why the Sn-rich phase is displaced from within the colonies to colony boundaries, rather than vice versa, is not altogether clear. In our eutectic Sn–Pb material the distribution of lamella orientation in colonies is quite random, so there is no unique correlation between the local strain state and the lamella orientation that can shed light on the observed "extrusion" process. In addition, due to the heterogeneous microstructure and the extremely large deformation involved, one *cannot* resort to the simple small-strain pure bending analysis that results in tensile and compressive stresses at, respectively, the convex and concave sides of the specimen. Nevertheless, a rationalization of the experimental finding is attempted in the following. The eutectic alloy featuring the colony structure may be thought of as composed of nominally spherical colonies surrounded by colony boundaries. The colonies themselves are relatively "hard" (due to the finely distributed and apparently confined Pb-rich layers) and the boundaries "soft". This conceptual picture is shown in Fig. 4, where a representative volume element (like the rectangle in Fig. 1) undergoing severe bending is schematically depicted. Due to the scarcity of the "soft" material (colony boundaries) that bears the most flow capability, the *inelastic* deformation has to be achieved by squeezing the "hard" regions near the concave side of the specimen so they are pushed towards the convex side (Fig. 4). The irrecoverable bent shape of the specimen thus becomes possible, while the overall colony structure is maintained. It is then apparent that the squeezed hard regions are under predominantly compressive stresses. Because the hard regions are actually colonies containing finely distributed Pb-rich lamella (incapable of extensive deformation) embedded in the Sn-rich matrix, it is natural that the Sn-rich material, in response to the compressive state, is extruded out of the colonies. This is particularly the case if one considers that our micrographs were taken very close to the AB line indicated in Fig. 1, where the most severe squeezing action took place.

The above conceptual model is conceivable inasmuch as it helps interpret the experimental observations in a straightforward fashion. Its details are subject to further experimental characterizations and numerical modeling. To this end, it is worth mentioning that the eutectic Sn–Pb alloy has long been identified as capable of superplastic deformation at elevated temperatures under appropriate strain rates [17,18]. The present study illustrates that severe plastic deformation without cracking can also be achieved in the form of fast room-temperature bending. More importantly, along with the macroscopic deformation the microstructure is altered, without the influence of thermally activated atomic diffusion.

4. Summary

We have carried out experiments on bending of the eutectic Sn–Pb alloy at room temperature, and observed microstructural changes associated with the fast deformation process. It appears that a change in microstructure is induced by this severe deformation. To a significant extent, the Sn-rich matrix phase is displaced from within the colonies to the colony boundaries. The Pb-rich layers themselves remain virtually unaffected. A micromechanical model is proposed, which takes into account the redistribution of colonies in response to the inelastic bending.

Acknowledgment

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Figure Captions

Fig. 1 Schematic showing the specimen shape after bending. Micrographs were taken on the cross section AB.

Fig. 2 Optical micrographs of the Sn–Pb alloy at different magnifications before bending.

Fig. 3 Optical micrographs of the Sn–Pb alloy at different magnifications after bending.

Fig. 4 Schematic of the proposed model showing the displacement of the colonies in accord with the macroscopic bending deformation.

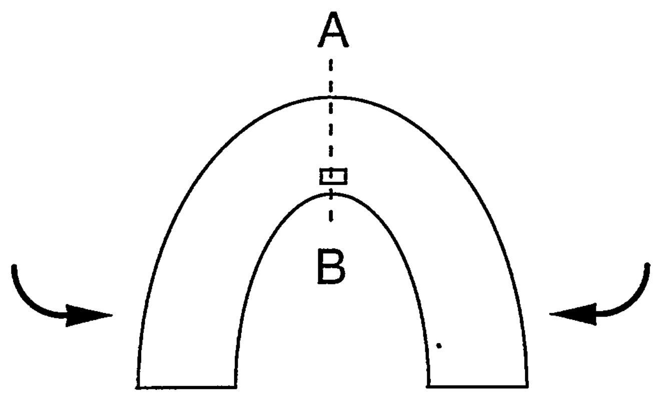
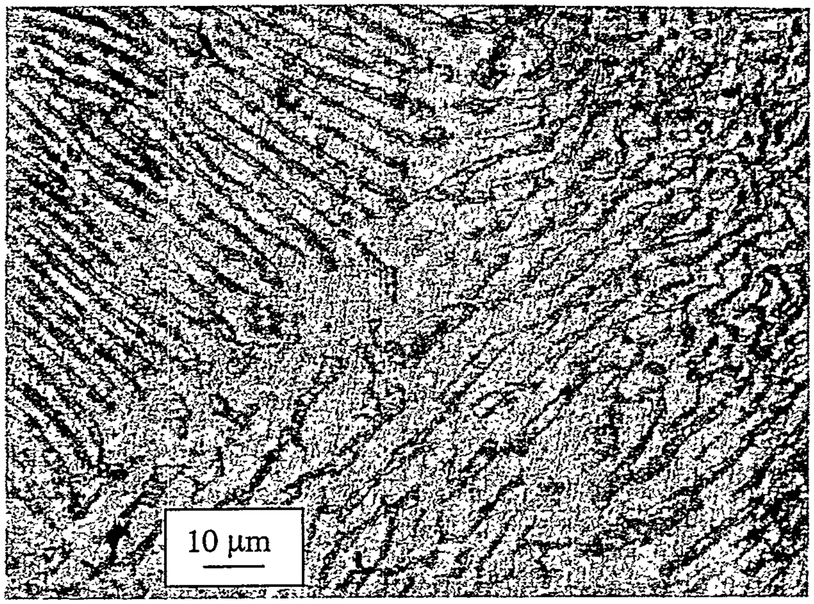
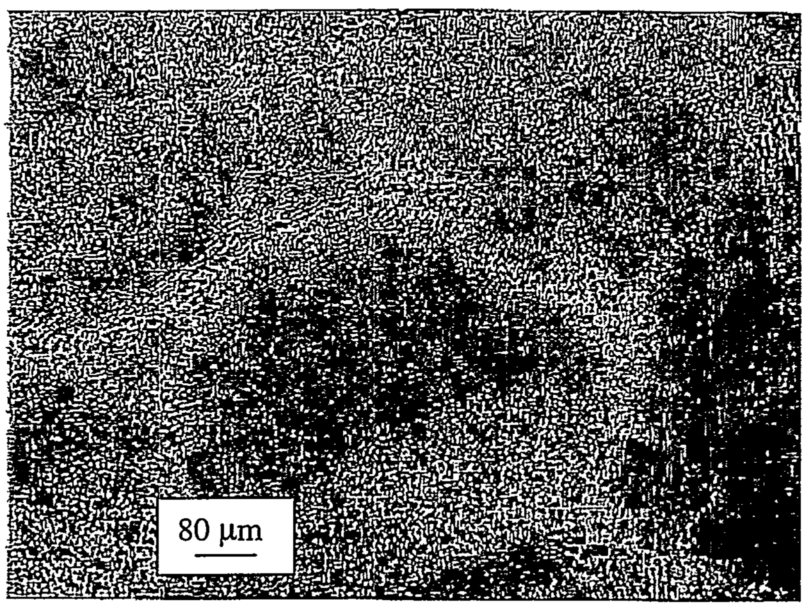


Fig. 1 Schematic showing the specimen shape after bending. Micrographs were taken on the cross section AB.

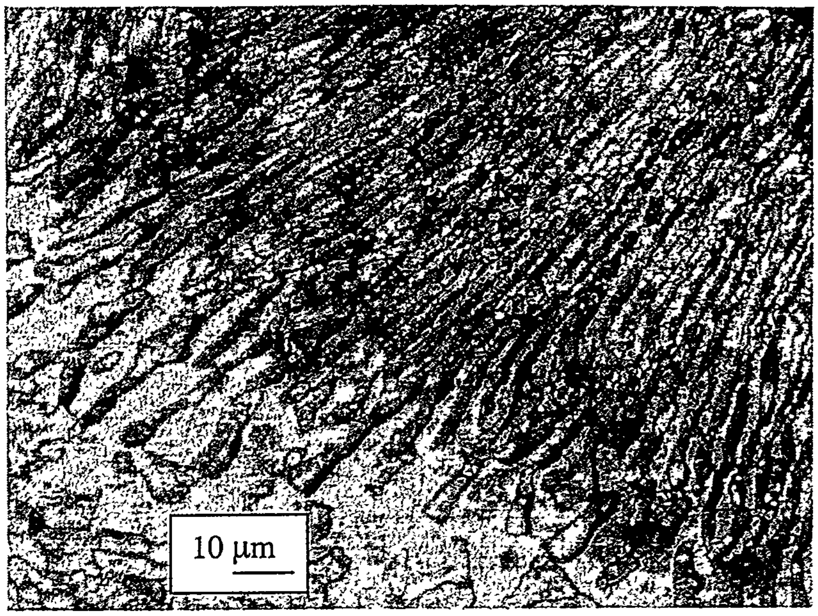


(a)

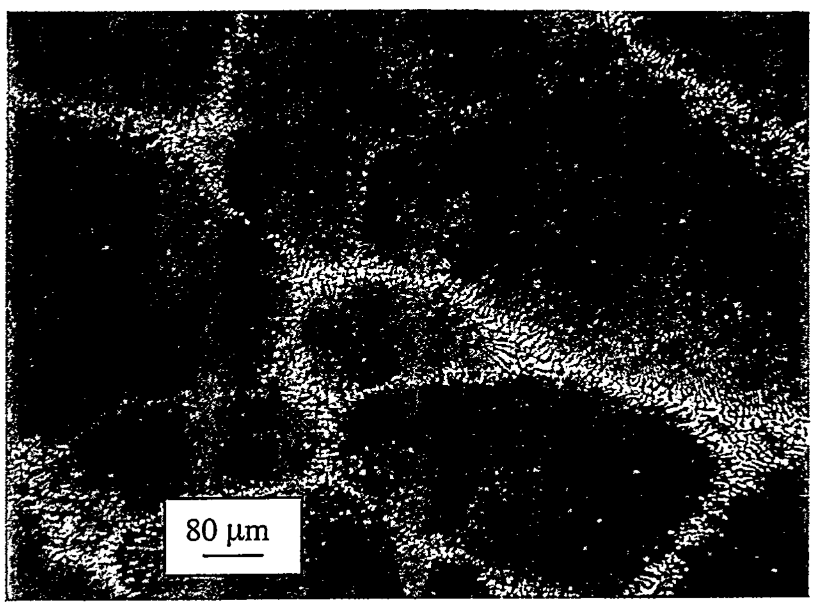


(b)

Fig. 2 Optical micrographs of the Sn–Pb alloy at different magnifications before bending.



(a)



(b)

Fig. 3 Optical micrographs of the Sn–Pb alloy at different magnifications after bending.

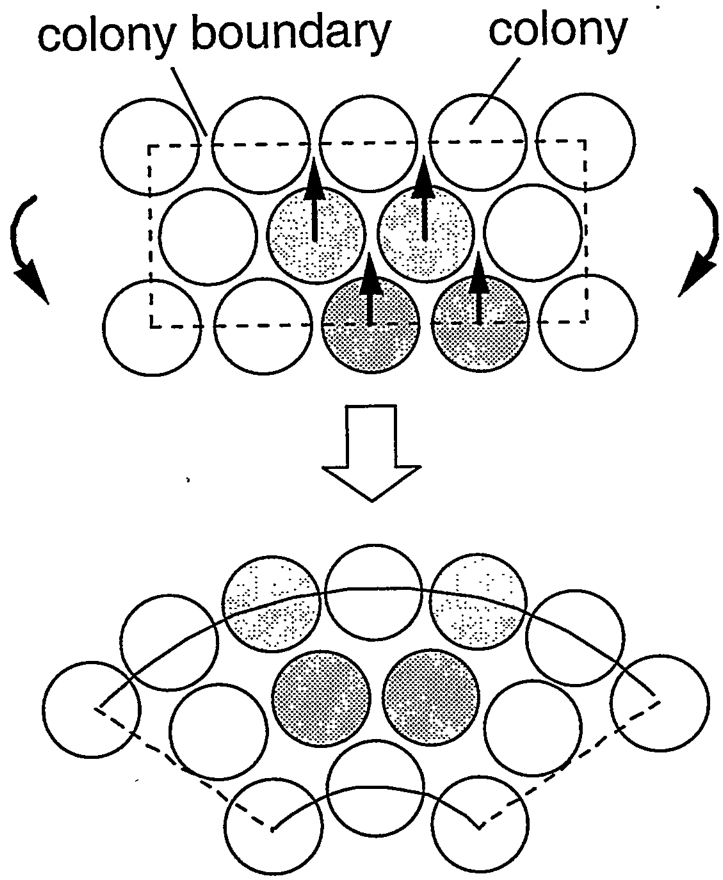


Fig. 4 Schematic showing the displacement of the colonies in accord with the macroscopic bending deformation.