

Thermal Fatigue Behavior of Sn-rich Pb-free Solders

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During device operation thermal fatigue damage occurs in solder joints due to the coefficient of thermal expansion mismatch between the different materials in the package. This damage accumulates and eventually leads to failure. In order to fully characterize the reliability of these lead-free solder alternatives, a fundamental understanding of the relationship between microstructure and fatigue behavior must be developed.

We have investigated the thermal fatigue behavior of Sn-rich solder joints at small length scales. Figure 1 shows a schematic of the sample geometry.

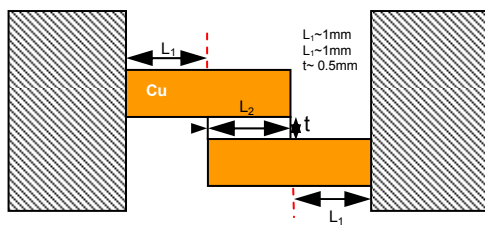


Figure 1: Thermal fatigue lap shear geometry.

Thermal fatigue testing was conducted at a fixed displacement by varying ΔT at a constant frequency of 10^{-3} Hz. Quantification of thermal fatigue deformation was accomplished by examining the following parameters: microstructure, stress/strain vs. temperature hysteresis, cycles to failure and fracture mechanisms. Figure 2 shows the applied strain range versus cycles to failure. Note that the Ag_3Sn dispersion strengthened systems (Sn-Ag and Sn-Ag-Cu) exhibit similar behavior, while Sn-Cu behaves similarly to pure Sn.

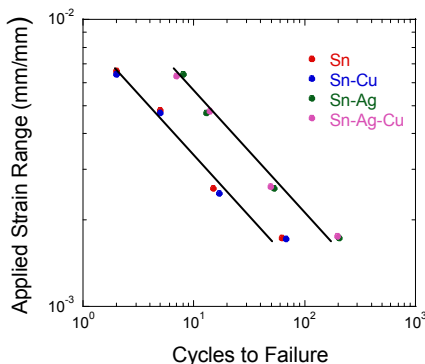


Figure 2: Strain range versus cycles to failure for various Sn-rich systems.

These results corroborate our recent creep deformation analysis conducted on these alloys.

Figure 3 shows the rapid cyclic-dependent softening of the Sn-rich material systems. This behavior is likely due to the growth of fatigue cracks and the development of persistent slip bands, as evident in Figure 4.

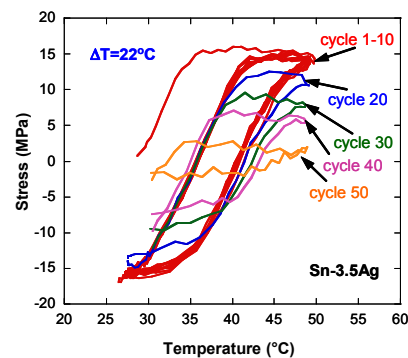


Figure 3: Evolution of stress versus temperature hysteresis behavior.

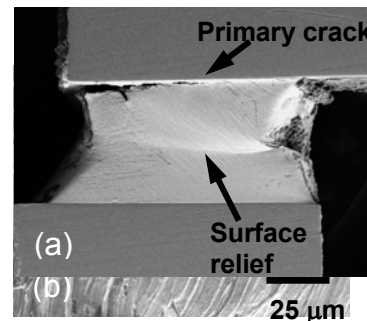


Figure 4: Damage accumulation during thermal cycling, highlighting (a) crack propagation and (b) persistent slip band formation.

Novel Rare-Earth Containing Lead Free Solders for Microelectronic Applications

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Pb-free solders pose new problems and challenges associated with their incorporation and reliability during service of electronic components. Recently, a new class of Pb-free solders has been discovered, with characteristics that make them interesting candidates for further study. These new alloys contain very small fractions of rare earth (RE) elements. It is believed that the new phases that form within these materials can be tailored (size, morphology, etc.) such that they produce a desired response in mechanical performance.

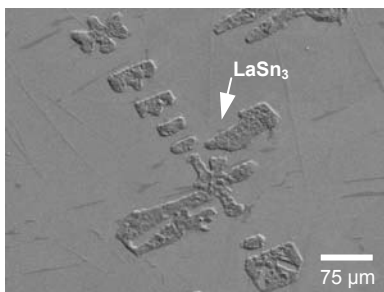


Fig. 1 SEM micrograph of LaSn_3 intermetallics formed in Sn-3.9Ag-0.7Cu-0.5La solder.

We are investigating a Sn-3.9Ag-0.7Cu system with trace amounts of lanthanum. It has been shown that with small additions of La an intermetallic phase forms in the solder, LaSn_3 . Fig. 1 is a representative scanning electron micrograph of the LaSn_3 intermetallic. Using a serial sectioning technique, the complex morphology of these intermetallics was investigated, revealing that they are in fact interconnected dendritic structures. Fig. 2 shows a 3-dimensional reconstruction of a small section of the microstructure, highlighting the LaSn_3 phase.

In addition to microstructure characterization, mechanical testing (monotonic shear and creep) is being conducted to examine the mechanical performance of these materials, and to understand the underlying mechanisms responsible for the observed behavior. Our group was the first to show that small amounts of La to Sn-Ag-Cu solder results in a substantial improvement in their ductility, with small penalties in strength. Fig. 3 shows a plot comparing the shear behavior of Sn-3.9Ag-0.7Cu, Sn-3.9Ag-0.7Cu-0.1La and Sn-3.9Ag-0.7Cu-0.5La. Note the dramatic increase in strain to failure in of the curves with the addition of La. Creep testing is currently being

conducted on single lap shear joints. Both bulk and small length scale behavior is being studied.



Fig. 2 Three-dimensional (3D) microstructure reconstructed from serial sections, highlighting the complex dendritic morphology of the LaSn_3

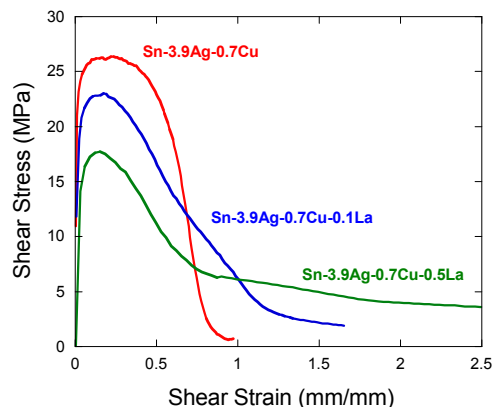


Fig 3. Shear stress vs. shear strain curves for Sn-3.9Ag-0.7Cu, Sn-3.9Ag-0.7Cu-0.1La and Sn-3.9Ag-0.7Cu-0.5La tested in monotonic shear.

References

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Damage Tolerant, Self-healing Shape Memory Alloy Fiber Reinforced Pb-free Solder Composites for Electronic Packaging

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A growing concern for lead-free solder alloys, such as Sn-Ag-Cu solder alloys, is their low ductility and toughness, relative to Pb-Sn. A method of improving the mechanical properties of lead-free solders is to create a composite containing shape-memory alloy fibers. Utilizing the superelastic transformation behavior of NiTi shape memory wire, it may be possible to deform a specimen beyond its yield stress, and have it return to its original dimensions upon removal of the external force (Fig 1).

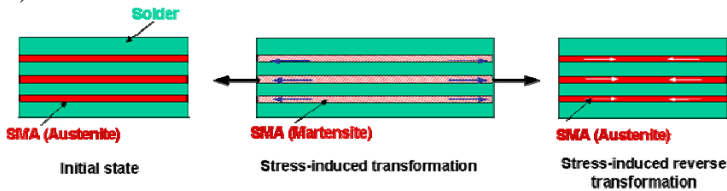


Fig. 1 Superelastic behavior of shape memory alloy lead-free solder composite

Shape memory alloys exist in two primary solid phases, martensite and austenite. At higher temperatures, the material takes on its parent FCC structure of austenite, while at lower temperatures BCT martensite is more energetically favorable. Superelasticity occurs just above the austenite transformation temperature. When an external stress is applied to the material a transition from austenite to martensite occurs, allowing the sample to deform with respect to the amount of stress applied. When the stress is released, the material reverts to austenite and returns to its original shape.

Single fiber, Sn matrix composites were being fabricated to evaluate the mechanical properties of these new materials. A very thin Sn-Ti intermetallic layer is formed during dipping of the fiber in liquid Sn. This reaction zone contributes to a strong bond between the components that enhances load transfer (Fig 2).

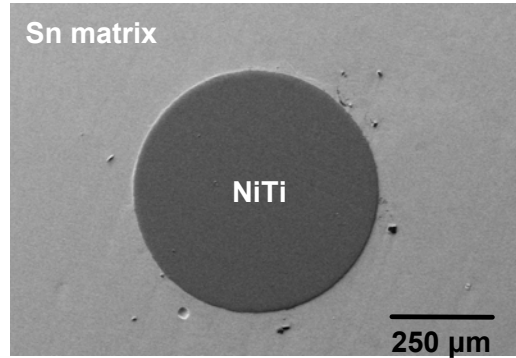


Fig. 2 FESEM cross-section of SMA NiTi shape memory wire in pure Sn matrix.

Figure 3 shows preliminary results of the composite behavior versus that of conventional Sn-Ag solder. Note that the SMA composite exhibits a large degree of recovery on unloading.

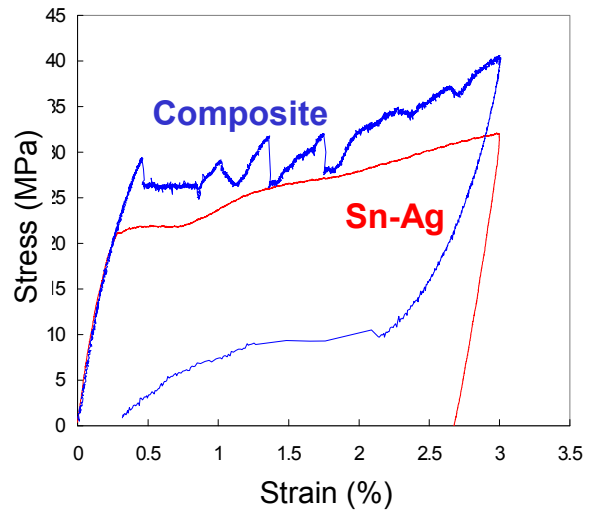


Figure 3. Stress-strain behavior of SMA solder composite versus Sn-Ag alloy. Note that the composite exhibits almost full recovery on unloading.

Three-Dimensional (3D) Microstructure-Based Modeling of Deformation in a Sn-rich Solder

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The deformation behavior of environmentally-benign Pb-free solders is controlled by their complex microstructure. Thus, a thorough understanding of microstructure of Pb-free solders is crucial. In particular, it is necessary to accurately characterize the size, distribution, morphology, and orientation of second phase intermetallics present in Sn-rich solders. Traditional metallographic techniques rely on two-dimensional images, such as optical and/or scanning electron micrographs, for representing the microstructure of a material. The size and aspect ratio of spherical microstructural features can be adequately characterized by two-dimensional (2D) circles. In the case of more complex geometries, however, 2D sections can significantly under- or overestimate their size and aspect ratio. In order to visualize the 3D microstructure, we have developed a technique whereby 2D sections of the material are used to reconstruct a 3D virtual microstructure. While visualization of the 3D microstructure of the material is important, prediction of the properties and local damage characteristics of the material is equally important. We have developed a methodology, whereby 3D microstructures can be incorporated into commercial finite element method (FEM) codes to model deformation behavior. Microstructure-based modeling of material properties is superior to traditional approaches, because it is capable of providing quantitative information, and more importantly, provides information relating to local damage phenomena in the material.

High purity cast ingots of Sn-3.5wt.%Ag solder were used in this study. Figure 1 shows a multi-particle reconstruction produced by 3D reconstruction software (MIMICS, Ann Arbor MI). This region consists of colonies of Ag₃Sn particles aligned within a given colony. The reconstructed virtual microstructure reproduces the actual size and morphology of Ag₃Sn.

The advantage of using a 3D microstructure-based model is shown by a comparison of the stress-strain curve of the 3D virtual microstructure simulation with experiment, Figure 2. The microstructure-based model predicts the experimental behavior quite well, while the spherical unit cell model predicts lower strength than the experiment. More importantly, the localized plasticity that results from the needle-like Ag₃Sn intermetallics can only be captured in the microstructure-based model, Figure 3. The local stress state of the Ag₃Sn particles for the three virtual microstructures, shown here, is inherently different, and is intimately linked to the relative orientation of the needles.

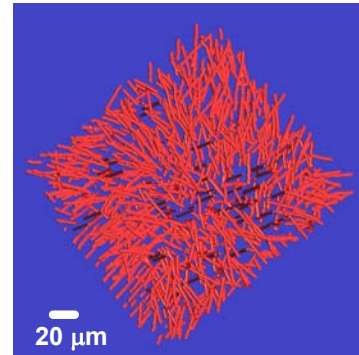


Figure 1: 3D microstructure reconstructed from serial sections: 3D model of the microstructure (180 μm x 170 μm x 60 μm).

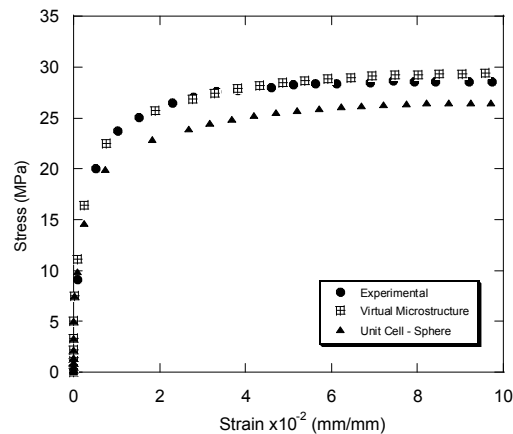


Figure 2: Comparison of stress-strain predictions from unit cell and 3D microstructure models with experiment. The 3D virtual microstructure is most accurate in predicting the experimentally observed behavior.

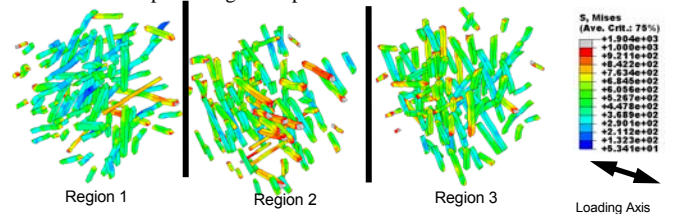


Figure 3: Von mises stress distribution in three different regions of the microstructure, highlighting the complex stress state due to randomly distributed needle-like Ag₃Sn intermetallics. Particles aligned parallel to the loading axis exhibited a higher stress due to more load transfer.

References

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