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Experimental determination of fatigue behavior of lead free solder joints in microelectronic packaging subjected to isothermal aging

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ABSTRACT

The effects of aging on the cyclic shear stress–strain and fatigue behavior of lead-free solders have been explored experimentally and have been presented in this paper. An experimental procedure has been developed for preparing Iosipescu shear specimens of SAC105 (Sn–1.0Ag–0.5Cu) lead-free solder, and the resulting solder joint specimens have been subjected to cyclic shear stress/strain loading at different aging conditions. A combination of four-parameter hyperbolic tangent empirical models has been used for the empirical fit of the entire cyclic stress strain curve. The fatigue life data were then fit using popular empirical failure criteria such as the strain-based Coffin–Manson model and the energy-based Morrow model. Evolution of shear hysteresis loop of SAC 105 with aging has been studied. Degradation of isothermal fatigue life due to aging has also been studied in this paper. A comparison between uniaxial fatigue data and shear fatigue data is shown and a good qualitative agreement has been found. Subsequent microstructure analysis has also been presented in the paper in support of isothermal aging effects.

1. Introduction

In the advanced microprocessor, millions of transistors are interconnected in an infinitely complicated way. With the increasing data points processing more inputs and outputs, thousands of solder joints are also involved for data transfer and powering. The questionable reliability of these solder joints in microprocessor chip packaging (whether mounting on substrate or printed circuit board) causes grave concern: failure of a single solder joint will cause electrical discontinuity and lead to ultimate failure. Therefore, accelerated failure of solder joints may result in substantial reduction of the reliability of the microelectronic packaging. In microelectronics, packaging solder joints are often subjected to thermal cycling, either during their application in products or during accelerated life qualification testing. Mismatches in the thermal expansion coefficients of the assembly materials, specially during power switching or periodic change of ambient temperature, cause the solder joints to be subjected to cyclic mechanical stresses and strains. Such cyclic loads lead to thermomechanical fatigue that results in damage accumulation, crack initiation and propagation, and eventual failure.

Many prior researchers have studied the cyclic stress–strain behavior of Sn–Pb solder materials. For example, Pao [1–3] used a two-beam geometry to successfully measure the thermo-mechanical hysteresis Sn–Pb solder and other Sn-based alloys. Hacke et al. [4] described a test assembly and reported both hysteresis and thermomechanical fatigue data for Sn–Pb solder. Since conversion to Pb-free solders in the global electronics assembly business appears dominant, studies on fatigue life of lead-free solders in microelectronic packaging have continuously been given prime importance in the recent years. The literature on the mechanical behavior of lead free solders has been reviewed by Ma and Suhling [5]. There are also several prior papers on the cyclic stress–strain and fatigue behavior of lead free solder materials. For example, Dusek et al. [6] studied the stress vs. strain behavior and evolution of the hysteresis loops of Sn3.5Ag0.5Cu solder during isothermal fatigue at several different temperatures (24, 30, 60, and 125 °C). They reported that with slow cycling, where creep and stress relaxation play dominant roles, the number of cycles to failure increases with higher temperatures. Herkommer et al. [7] have developed a damage model that is capable of predicting material behavior under both mechanical shear cycling and thermal cycling loading conditions. Zhang and Dasgupta [8–9] have discussed the mechanical and thermal cycling durability of selected lead-free solders (Sn3.9Ag0.6Cu, Sn3.5Ag, and Sn0.7Cu), and developed a mechanical fatigue damage criterion. They demonstrated good correlation between their damage criterion and cycles to failure under different strain rate and temperature conditions.

Whitelaw et al. [10] have determined the parameters of the Bonder–Partom model from uniaxial cyclic stress–strain tests for both lead-free solders and Sn–Pb solder. They have also verified the model under isothermal thermo-mechanical cycling conditions. Korhonen and coworkers [11] conducted uniaxial cyclic tests under various working temperatures for near eutectic Sn–Ag–Cu alloy to understand the isothermal fatigue behavior. Kanchanomai et al. [12] performed uniaxial strain controlled cyclic test to investigate fatigue failure and mode II crack growth behavior of Sn–Ag eutectic solder alloy for different strain

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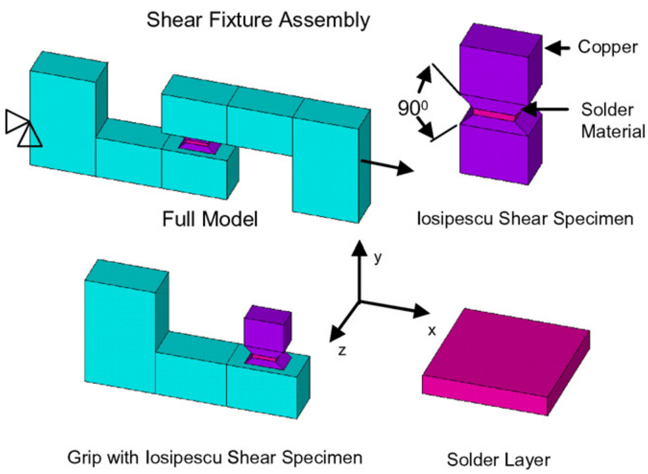

Fig. 1. Modified Iosipescu shear test specimen and loading fixture.

ranges, load drop parameters, and times to failure. Fatigue failure behavior and cyclic creep deformations in lead free solders were also observed by Shang et al. [13], where the fatigue lives of different lead-free solders were related to cyclic stress amplitude, number of cycles, stress ratio, loading frequency, temperature, alloy composition, and microstructure. Both uniaxial cyclic tests and shear cyclic tests were carried out by Andersson et al. [14] to establish a comparison of isothermal mechanical fatigue properties of lead free solder joints and bulk solders. Fatigue tests were performed by Pang et al. [15] for SAC387 (95.5Sn–3.8Ag–0.7Cu) and Sn–Cu (99.3Sn–0.7Cu) solder alloys. In their study, the Coffin–Manson model and the Morrow model were used to describe the low cycle fatigue behavior of those materials.

Several different shear testing techniques have been used for solder joints. These methods include the Iosipescu technique [8–9,16–19], ring-and-plug shear [20–21], single lap-shear [22–24], double lap shear [25], and solder ball shear [26]. Although no method provides an exact state of uniform pure shear stress in the test sample, the Iosipescu method has been popular due to its widespread use for shear testing of fiber-reinforced composite materials. Zhang et al. [8–9,18] have used an Iosipescu-type specimen to perform cyclic testing and creep testing of solders in shear. The uniformity of the shear stress/strain state in their test samples has been explored by Mukherjee and Dasgupta [19]. A similar modified lap shear technique using an Iosipescu shear specimen has been developed by Mustafa [27].

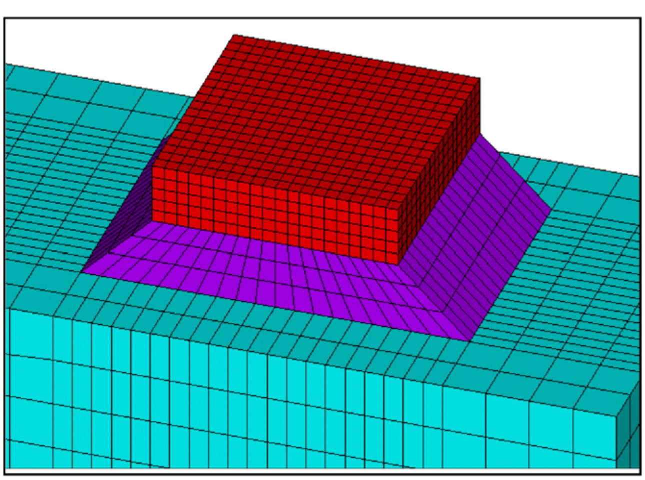

Fig. 2. Finite element model near solder layer.

Table 1
Anand parameter for reflowed SAC105 solder.

Anand par.	Unit	SAC105
s_o	MPa	7.5
Q/R	1/K	8850
A	s^{-1}	6900
ξ	–	4
m	–	0.215
h_o	MPa	137,500
$\hat{s}$	MPa	25.1
n	–	0.0062
a	–	1.96

Several studies have been performed on degradation of solder material properties when the alloys are exposed to isothermal aging. For example, aging has been demonstrated to reduce BGA ball shear strength [28], solder elastic modulus [29], drop reliability [30], fracture toughness [31], and shear strength [32]. Mustafa et al. have studied the aging-induced changes occurring in the cyclic stress–strain behavior of lead free SAC solders for both tension/compression [33] and shear [27] loadings. The effects of aging on the constitutive of lead free solder have also been extensively investigated by the authors [34–45]. In initial work, room temperature (25 °C) and elevated temperature (50, 75, 100, and 125 °C) aging were shown to severely degrade the mechanical properties and creep behavior of SAC alloys by Ma and Zhang et al. [34–37]. Zhang et al. have also explored aging effects in mixed solder alloys (SAC and Sn–Pb) [38], while Cai and co-workers [39] have demonstrated that such aging effects can be reduced in lower Ag content alloys through the use of dopants (i.e., SAC-X). In addition, Zhang et al. [40–41] have shown that prior aging causes large reductions in the reliability of BGA test assemblies subjected thermal cycling accelerated life testing. Motalab et al. [42–43] have included aging effects in the Anand constitutive model and energy density based failure criterion for SAC solders, and then used these theories with finite element analyses to predict the thermal cycling life of aged BGA assemblies. Good correlations were achieved with the measured lifetimes from references [40–41]. Finally, Hasnine et al. [44] have used nanoindentation to study the evolution of mechanical properties and creep rates in BGA solder joints subjected to aging, while Lall and co-workers [45] have investigated changes in the high strain rate behavior of SAC solders subjected to aging.

In this investigation, the effects of aging on the cyclic shear stress–strain and fatigue behavior of lead-free solders have been explored. A procedure has been developed for preparing lead-free solder Iosipescu shear specimens, and the resulting samples have been subjected to cyclic shear stress/strain loading at different aging conditions. The entire cyclic stress–strain curve was fit mathematically, and definite integration was used to calculate the hysteresis loop area (energy dissipated per cycle) for a given strain limit. Samples were cycled to failure using strain controlled cyclic loading for a variety of strain limits. Fatigue failure was defined to occur when there was a 50% peak load drop during mechanical cycling. Park and Lee [46] showed that there were abrupt increases in the resistance of BGA solder joints at 50% load drop during fatigue testing.

The present paper illustrates the measured results for SAC105 (Sn–1.0Ag–0.5Cu) lead free solder. Prior to testing, the specimens were aged (preconditioned) at 125 °C for various aging times, and then the samples were subjected to shear cyclic loading at room temperature (25 °C). The evolution of the solder hysteresis loops with aging was characterized and modeled using the recorded cyclic stress–strain curves. Using the recorded fatigue data, the variation of the parameters in the Coffin–Manson and Morrow fatigue models with aging have been determined. Results obtained from fatigue tests of uniaxial specimens were also compared to the shear results from the Iosipescu shear samples to establish a good qualitative and quantitative agreement.