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Computational modeling of creep-based fatigue as a means of selecting lead-free solder alloys

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ABSTRACT

The primary aim of this investigation was to understand the effect of temperature fluctuations on a number of various solder materials namely SAC105, SAC305, SAC405 and Sn–36Pb–2Ag. To achieve this objective, three different classic joint assemblies (a ball joint, a test specimen joint and finger lead joint) were modeled which provided the foundation for the creep and fatigue behaviors simulation. Anand's viscoplasticity as a constitutive equation was employed to characterize the behavior of solders numerically under the influence of thermal power cycles (80–150 °C) and thermal shock cycles (−40 to 125 °C). To extend the research outcome for industrial use, two additional research activities were carried out. One of them was to obtain lifetime-predictions of solder joints based on Coffin Manson concept. The other one focused on parameterization to obtain the ideal solder thickness under the consideration of plastic strain and economic benefit.

1. Introduction

Solders, made of fusible metal alloys, are used to join two parts together in an electronic assembly. Apart from the mechanical bonding, they also provide an electrical interconnection between the two parts [1]. Due to the differences in material properties such as the coefficients of thermal expansion (CTE) of the metal parts, thermal stresses arise in the assembly, which consequently lead to a reduction in the lifetime of the joint [2]. In thermal fatigue, there is a transition from fatigue failure to creep failure as the temperature increases (creep dominates at higher temperature) and the situation becomes even more complicated if both fatigue and creep interact with each other during thermal or power cycling of electronic packages.

Lead based solders have been used for many years in the industry because of their good material properties. Due to the new legislation "Restriction of Hazardous Substances Directive" in 2006, lead based solders are gradually being replaced by lead free solders in the electronic industry [3]. At present, the creep behavior and lifetime expectation of these lead free solders are not well understood under the influence of temperature fluctuations. Therefore, much effort is being expended in time-consuming experimental investigations to obtain data on the creep behavior and the lifetime expectation.

The literature review highlighted three typical but different joint assemblies (a ball joint, a test specimen joint and finger lead joint) for which clear joint geometry, solder properties and loading cycles were given, in conjunction with experimental test data. With this combination of test case information, it was possible to run a series of simulations using Anand's viscoplasticity model to gain information about the impact of temperature fluctuations on different solders. Empirical methods were then used to predict the life of these joints in terms of the number of cycles to failure ($\mathbf{N_f}$).

In our view this paper will provide a starting point from which other researchers can obtain geometry, material properties and boundary conditions to benchmark their own use of computational creep models of lead-free solders. In comparison to the previous work, this investigation provides a good assessment of various solder behaviors in different geometries and load cycles under a constant simulation settings.

2. Modeling methodology and benchmark simulations

A printed circuit board (PCB) is an electronic assembly in which electronic chips or leads are fastened via solder joints [4]. Such assemblies play an important role for computers [5] and other

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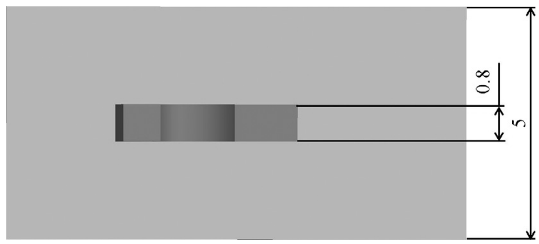

Fig. 1. Finger lead model (top view).

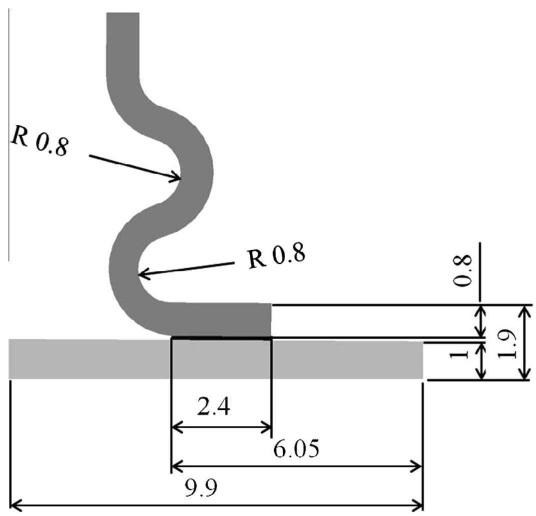

Fig. 2. Finger lead joint (front view).

appliances. Therefore, three of the most widely used solder joint models were chosen and designed after reviewing current literature. Figs. 1 and 2 illustrate the finger lead joint made of a copper finger lead, a thin solder layer (thickness of 200 μm, length of 2400 μm and width of 800 μm) and a copper plate. The test specimen joint (Fig. 3) whose geometry was also used by [6], consisted of two identical sized copper plates and a thin solder layer (thickness of 180 μm, width of 1000 μm and length of 3000 μm). The ball solder joint (Fig. 4) as described in [7,8] is used in the Ball Grid Array (BGA) assembly, and consists of two identical sized copper plates and a solder ball (width of 0.484 mm, top diameter of 0.484 mm and Ball diameter of 0.744 mm).

Modeling is an extremely useful tool in the early design stage to reduce the cost and time of testing. The accuracy of the results significantly depends on the choice of the constitutive equations employed and the material parameters used for modeling [9].

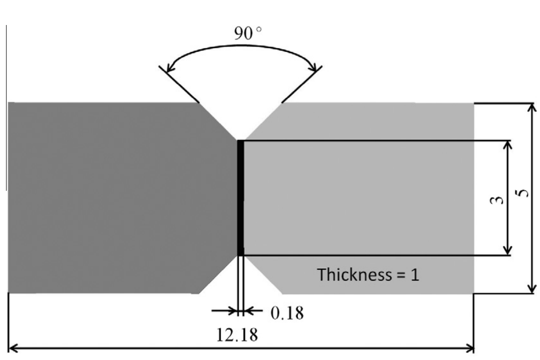

Fig. 3. Test specimen joint.

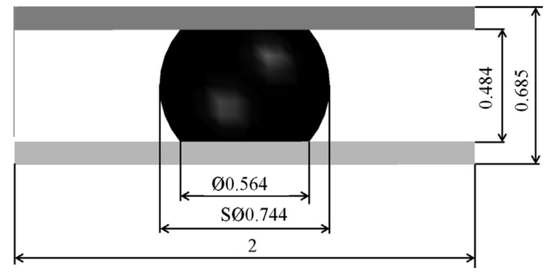

Fig. 4. Ball joint.

2.1. Visco-plastic models

In general, the unified viscoplastic model considers the inelastic strain rate variation by using a flow law and the variation of the state variables described by evolution equations. Some unified viscoplastic models are the Anand model, McDowell model, Basaran et al., Wei et al. and Chaboche's model. The Anand model is one of the simplest models which can be implemented in the FE codes. Chaboche's viscoplastic model includes combined kinematic/isotropic hardening effects whereas Anand model considers only the isotropic hardening effects. McDowell's model comprises the features of Anand model and Chaboche's model. It uses the Zener Hollowman parameter for creep activation mechanisms and combined kinematic/isotropic hardening [10].

2.2. Anand model

Anand is a common alternative model to creep for simulation of viscoplastic behavior in solders. Many previous simulations have been carried out with the Anand model and published [11,12]. The Anand model is expressed by a flow equation and three evolution equations, as written mathematically below.

Flow equation

$$\dot{\varepsilon}_{\mathbf{p}} = \mathbf{A}\ \exp\left(-\frac{Q}{RT}\right)\left[\sinh\left(\xi\frac{\sigma}{s}\right)\right]^{1/\mathbf{m}} \tag{1}$$

where $\dot{\varepsilon}_{\mathbf{p}}$ represents the inelastic strain rate, **A** is a pre-exponential factor, Q is used for the activation energy, R stands for gas constant, T is absolute temperature, ξ is the multiplier of stress, σ is the equivalent stress, **m** is strain rate sensitivity.

Evolution equations

$$\dot{\mathbf{s}} = \left\{\mathbf{h}_0(|\mathbf{B}|)^{\mathbf{a}}\frac{\mathbf{B}}{|\mathbf{B}|}\right\}\dot{\varepsilon}_{\mathbf{p}} \tag{2}$$

where

Table 1
Anand parameters for various solders [12,13].

Symbol	Units	SAC105	SCA305	SAC405	Sn36Pb2Ag
$\mathbf{S}_0$	MPa	2.348	2.150	1.3	12.41
Q/R	K^{-1}	8076	9970	9000	9400
A	S^{-1}	3.773	17.994	500	4000000
ξ		0.995	0.350	7.100	1.5
M		0.445	0.153	0.300	0.303
$\mathbf{h}_0$	MPa	4507.5	1525.98	5900	1379
$\hat{\mathbf{S}}$	MPa	3.583	2.536	39.4	13.79
N		0.012	0.028	0.030	0.07
A		2.167	1.690	1.100	1.3