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Experimental and numerical investigation on the reliability of leadfree solders

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Abstract

To assess the lifetime of leadfree solder joints, it is necessary to investigate their creep and failure behavior under cyclic thermo-mechanical loading. In connection with finite element analyses the use of an appropriate material model is necessary. The following paper reports on the implementation of a specific version of the viscoplastic constitutive model of Chaboche in the FEM-code ABAQUS, the experimental program for the identification of the material parameters of a Sn–Ag–Cu solder and a comparison of some numerical and experimental results.

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1. Introduction

Since the 1st of July 2006 it is prohibited to bring plumbiferous electronic products on the market according to the EU-guidelines WEEE (2002/96/EC) and RoHS (2002/95/EC). Therefore, the replacement of plumbiferous solder alloys by leadfree alternatives was the main goal of the last years. Thus research was focused on finding leadfree solutions showing a similar behavior like the plumbiferous solders and being able to ensure the reliability of electronic products. The investigations of the last years revealed that solders based on tin and silver are the most promising candidates to substitute the plumbiferous ones. Especially the alloy Sn96.5Ag3.5 and different compositions of the ternary system of SnAgCu show good properties with respect to creep resistance and reliability, see e.g. [1–3]. Concerning the reliability of the solders the thermo-mechanical fatigue is the main problem that is a consequence of the mismatch of the coefficient of thermal expansion (CTE) of the jointed partners in combination with the in service loads. These loads are predominantly temperature cycles due to power cycling of the electronic component or a result of temperature changes of the

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environment. The changing temperatures cause thermal and mechanical strains [4]. With the increasing miniaturization of electronic devices less solder material is able to absorb these strains resulting in thermally induced low cycle fatigue (LCF). Thus there were plenty of investigations for lead containing solders in the field of LCF. Here the well known Coffin–Manson Relationship (CMR) was used to determine the lifetime of solder joints. With the usage of the new tin based solders this approach has to be verified. In [5,6] the LCF behavior of cask tensile specimens of three solders including Sn96.5Ag3.5 were investigated. It was shown that the frequency-modified CMR, which takes the strain rate sensitivity into account, can describe the LCF behavior of the Sn96.5Ag3.5 solder. In [7] the Morrow energy model was used to describe the LCF-behavior of ball grid array solder joints made of Sn95.75Ag3.5Cu0.75 solder to determine their life time in mixed mode loading condition. All in all many experimental investigations can be found in the literature [8–11], concerning creep properties in connection with aging of the solder, effects of cooling rates, different metalizations, fatigue, etc. However, there is still a lack of an appropriate constitutive model that can describe the complex thermo-mechanical behavior of the leadfree solders including strain rate sensitivity, primary and secondary creep [12]. First of all this behavior has to be described by a material model to make reliable FE-simulation of electronic components with the solder joints possible. Such a model has to account for the strong time dependent mechanical behavior of leadfree solders, i.e. increasing stresses with increasing strain rate, creep, relaxation and a nonlinear cyclic plastic hardening with recovery effects, all of which is a function of temperature. For this purpose a modification of the unified Chaboche model was chosen, using two back stresses with dynamic and static recovery to describe the behavior of the solders. It was implemented as a user defined material subroutine (UMAT) into the commercial FEM-code ABAQUS under the assumption of small deformations.

To identify the material parameters an experimental setup was developed, where double lap-shear specimens could be tested under various conditions. The experimental program contained monotonic experiments with different strain rates followed by relaxation, cyclic tests and creep tests. All tests were realized at four different temperatures to investigate the temperature dependence of the material parameters. For the parameter identification the general equations of the used material law were simplified to pure shear. The integration of the resulting equations was done using an explicit 2nd order Runge–Kutta-time integration scheme. This scheme is implemented to simulate the shear experiments for the parameter identification to compare the numerical results with the experimental data. By means of an error measure the quality of an assumed parameter set is estimated. An algorithm is developed to minimize this error norm achieving the optimal material parameters.

2. Viscoplastic constitutive model

Within the framework of the unified Chaboche model [13,14] the strain tensor consists of an additive decomposition of an elastic and an inelastic part. In the case of changing temperatures a thermal part arises too

$$\varepsilon_{kl} = \varepsilon^{\mathrm{e}}_{kl} + \varepsilon^{\mathrm{p}}_{kl} + \varepsilon^{\mathrm{th}}_{kl}. \tag{1}$$

The inelastic part is denoted by a single superscript p, which indicates time-dependent plastic deformation in the framework of viscoplasticity. The stresses are related to the elastic strains by Hooke's law

$$\sigma_{ij} = E_{ijkl}\varepsilon^{\mathrm{e}}_{kl}. \tag{2}$$

Using the Lame's coefficients λ and μ the isotropic elasticity tensor is given by

$$\begin{aligned} E_{ijkl} &= \mu(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) + \lambda\delta_{ij}\delta_{kl} \\ \lambda(T) &= \frac{vE(T)}{(1+v)(1-2v)} \\ \mu(T) &= G(T) = \frac{E(T)}{2(1+v)}. \end{aligned} \tag{3}$$