International Journal of Solids and Structures 000 (2016) 1–12

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Modeling of intergranular thermal fatigue cracking of a lead-free solder joint in a power electronic module

Van-Nhat Le[a], Lahouari Benabou[a,*], Quang-Bang Tao[a,b], Victor Etgens[a]

[a] LISV, Université de Versailles Saint-Quentin-en-Yvelines, Versailles 78035, France
[b] Department of mechanical engineering, University of science and technology, The university of Danang, VietNam

ARTICLE INFO

Article history:
Received 2 July 2016
Revised 21 October 2016
Available online xxx

Keywords:
Intergranular fatigue fracture
Lead-free solder
Crystal plasticity
Cohesive zone
Finite element modeling

ABSTRACT

Fatigue of lead-free solder joints remains the most critical concern in thermo-mechanical reliability of high power modules. Due to size miniaturization requirements, fatigue properties become strongly affected by features of the solder joint microstructure. Phenomenological fatigue models based on effective material properties at macro-scale only grossly predict the engineering lifetime for some specific boundary conditions while ignoring the important effects of the microstructural mechanisms of deformation. In this study, a 3D microstructure-informed model for reproducing the intergranular fatigue crack in the solder joint of a power module is developed. The submodeling technique is applied in order to investigate accurately the critical zone of the solder joint with reasonably reduced computational time. In the submodel, the anisotropic elasticity and crystal plasticity constitutive laws are integrated for the bulk grain material, while the decohesion at grain boundaries is modeled by the cohesive zone approach. The needed crystal plasticity parameters are calibrated using the Berveiller–Zaoui transition rule to fit tensile test data for the so-called InnoLot solder alloy, and physically-based concepts are used to estimate the cohesive zone parameters at the grain scale. Simulations demonstrate how fatigue cracking occurs and propagates at grain boundaries in the solder joint. A criterion is then presented to estimate the fatigue lifetime of the entire solder joint, based on specific quantities predicted numerically.

1. Introduction

Insulated-gate Bipolar Transistor (IGBT) is extensively used in automotive, aerospace and alternative energy applications in response to the increasing demand of electrical energy management systems in recent years (Lu et al., 2009). Future trends in the domain of power modules in terms of miniaturization pose a major challenge for the reliability of the IGBT packaging. Reliability depends not only on the design parameters of the module but also on the operating conditions during its lifetime. The multi-material structure of the IGBT module is illustrated in Fig. 1, with each material having its specific coefficient of thermal expansion (CTE). Under thermal cyclic loading, the module exhibits several modes of fracture such as wire bonding fatigue, substrate delamination, chip metallization degradation, or solder joint fatigue (Benabou et al., 2014). The latter mode, which causes the solder layer to experience crack growth with cycle number, remains one of the most critical concern for the integrity of the whole package.

In order to predict the fatigue of the solder joints based on these alloys, several phenomenological models of fatigue have been developed coupling experimental thermal/mechanical cycling test data with finite element modeling (FEM). These semi-empirical models generally ignore the fundamental microstructural mechanisms which are responsible for damage observed at the scale of the component or the structure. They can be divided in four major categories: *strain*-based, *stress*-based, *energy*-based and *damage*-based fatigue approaches. A review of solder joint fatigue models is done in detail in Lee et al. (2000). Even though such approaches are of practical use for reliability assessment in the context of electronic engineering industries, many studies prove that they may still fail to accurately predict fatigue lifetime of solder joints which are used in complex electronic assemblies and are subjected to highly variable thermal loading (Ekpu et al., 2014; Grieu, 2011; Lee and Jeong, 2014). The material parameters, involved in this type of approaches, are simply estimated by performing conventional cycle fatigue testing. However, the identified parameters are often found to be strongly related to the specificities of the experiments conducted for a particular application (sample geometry and size, type of loading, etc.). Another restriction lies in the fact that features of the microstructure are not taken into

* Corresponding author.
E-mail address: lahouari.benabou@uvsq.fr (L. Benabou).

http://dx.doi.org/10.1016/j.ijsolstr.2016.12.003
0020-7683/

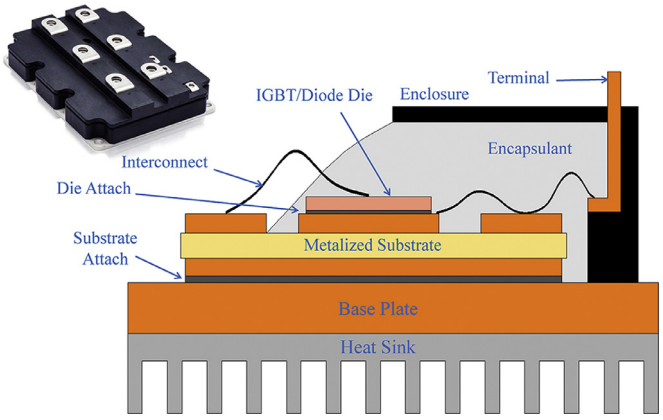

Fig. 1. Schematic of an IGBT power module.

account by a phenomenological approach. In this regard, it should be mentioned that solder joints, used in microelectronic packages (ball grid array/interface layer), have a very small thickness in the order of only a few grains; which is much smaller than the dimensions of the bulk solder specimens used in fatigue testing. As a result, macroscopically founded constitutive models, like the Anand law (Anand, 1985) or the model of Lemaitre–Chaboche (Lemaitre et al., 2009), may present some drawbacks when used in such circumstances where size effects are expected to have a dominant influence. Thus, improvement of the lifetime predictions for the solder joints will increasingly require integrating the important microstructural characteristics into the modeling.

To date, with the present-day availability of cheaper and powerful computational tools, the crystal plasticity model (CPM) has been successfully implemented in many FE codes as a user subroutine for describing the mechanism of plastic slip in the crystals, as well as for studying the overall deformation of the solder joint considered as a polycrystalline aggregate. The CP theory allows predicting in particular the local stress and strain fields in the grains under application of complex boundary and loading conditions. Furthermore, the use of the CP theory can also prove helpful, when coupled with experimental measurements, to identify local material parameters or small-scale deformation mechanisms. The approach was initially formulated by Taylor (1934) and the constitutive equations for the visco-plastic behavior of a single crystal were formulated by Mandel (1965) and Hill (1966), based on continuum mechanics. Extension to finite strain formulation was then made by Hill and Rice (1972), and Asaro and Rice (1977), before FE implementation of the model done by Huang (1991). Investigations of crack growth in polycrystalline materials are numerous and deal with various material applications. A 3D geometrical model was developed, for example, in order to study the brittle fracture of polycrystalline zinc in Hughes et al. (2007). Musienko and Cailletaud (2009) reported a coupled numerical model accounting for both grain boundary damage through combination of opening and sliding deformation, and trans-granular fracture resulting from normal stresses. Application of CP to study solder joint deformation has also been made in the context of finite element analysis (FEA). Gong (2008) proposed a CP-based description of the SnAgCu solder joint behavior under thermal cycling loading conditions. Bieler and Telang (2009) examined the various slip systems in a shear lap lead-free solder joint by conducting simulations with the help of the viscoplastic CPM developed by Lebensohn and Tomé (1993). Darbandi et al. (2014) indicated that the CP approach has the ability to predict the heterogeneous strain observed in the physical samples. This paper suggests also that CPM can be employed as an efficient tool to predict damage initiation and evolution with thermal cycles.

The effect of the different crystallographic orientations on the fatigue behavior of tin has been studied by Kariya et al. (2012), showing that the low cycle fatigue lifetime of a single crystal of β-tin can be evaluated by the inelastic strain energy density regardless of crystallographic orientation. Experimental observations indicate that fatigue failure in the lead-free solder joint appears prone to occur at grain boundaries (Erinc et al., 2008; Matin et al., 2004; Subramanian, 2007). This suggests that grain boundary properties are key parameters in the behavior of solders under fracture. To model this type of failure occurring at interfaces in materials, the cohesive zone model (CZM) has proved effective. The method is widely known and mostly used because of its well-established implementation in the computation codes, and it has been applied in a variety of applications to study delamination in structural joints (Benabou et al., 2013). In recent studies, it was used to evaluate the intergranular fracture as, for example, in Luther and Könke (2009) and Benedetti and Aliabadi (2013) where the authors proposed a CPM coupled with the CZM to describe crack growth at grain boundaries in polycrystalline materials under deformation. An analytic homogenization model, based on the CZM, has recently been reported by Benabou and Sun (2015) to study grain boundary decohesion in a Cu-Ni-Si alloy. Slack and Sadeghi (2011) developed an explicit FE formulation for intergranular fatigue damage in rolling contacts where grain boundary failure is treated using a CZ approach.

The objective of this paper is to provide a numerical methodology for reproducing initiation and propagation of intergranular fatigue cracking in a solder used in a power module. A micromechanical FEM, coupling CP with the CZ approach, is developed to reproduce anisotropy and plastic slips in the β-tin crystals on one hand, and failure at grain boundaries on the other. The CP parameters are fitted out with the help of the Berveiller-Zaoui homogenization scheme using experimental data from testing of InnoLot solder specimens, while the parameters for the CZM are estimated based on physical quantities related to concepts of small-scale material fracture.

The paper is structured as follows. In the Section 2, the CPM and the associated parameter calibration procedure are presented for the so-called InnoLot solder studied in this work. The CZM is described in Section 3, as well as its application to grain boundary decohesion in the solder joint. Sections 4 and 5 are dedicated to the FE procedure and the analysis of the results, respectively.

2. The crystal plasticity model for β-tin

2.1. Constitutive equations for crystal plasticity

The CP approach, initially developed by Asaro (1983) and Asaro and Rice (1977) for the face-centered cubic (fcc) lattice, was adjusted and applied in this work to describe the micro-scale viscoplastic behavior of the solder material. In the formulation of the model, the shear rate for each slip system is obtained before being used as a contribution to the total plastic deformation of the single crystal. Interactions between the slip systems, as well as relationships between the microscopic shear rates and the macroscopic plastic strain rate are briefly described below. The plastic slip rate for the αth slip system is given by the viscoplastic power law relation of Hutchinson (1976) as follows:

$$\dot{\gamma}^{(a)} = \dot{\gamma}_0 \cdot \left(\frac{\tau^{(a)}}{g^{(a)}} \right)^n \operatorname{sgn}(\tau^{(a)}) \tag{1}$$

where $\dot{\gamma}_0$ is the reference strain rate; $\tau^{(a)}$ and $g^{(a)}$ are the resolved shear stress and the slip system strain hardness, respectively; and

Please cite this article as: V.-N. Le et al., Modeling of intergranular thermal fatigue cracking of a lead-free solder joint in a power electronic module, International Journal of Solids and Structures (2016), http://dx.doi.org/10.1016/j.ijsolstr.2016.12.003