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Identification of damage and fracture modes in power electronic packaging from experimental micro-shear tests and finite element modeling

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ABSTRACT

Micro-shear tests are performed in order to characterize the mechanical behavior and the fracture of the chip/metallized ceramic substrate assemblies of power electronic devices. These assemblies are elaborated using three types of junctions: *AuGe* solder/*Au or Ag* finish, transient liquid phase bonding (TLPB) *AgIn*/*Ag* finish and *Ag* nanoparticles/*Au* or *Ag* finish. The experiments are associated to finite element simulations of both nano-indentation and micro-shear tests. The mechanical behavior of the different assembly interfaces is represented using an in-built cohesive zone model (CZM) available in the user friendly finite element code Abaqus®. It is worth noting that the fracture mechanisms observed during the test and service periods of the power electronic packaging are not only due to the debonding at the interfaces but also to the initiation and growth of voids in the joint. Therefore, in addition to the CZM model, Gurson-Tvergaard-Needlmann (GTN) damage model is used in combination with the Rice bifurcation theory to correctly describe the fracture in the joint and, therefore the overall fracture mechanism of the entire junction. The simulation results are compared with the experimental force displacement curves and the SEM observations in order to assess the implemented model.

1. Introduction

One of the challenges in high temperature power electronics is the reliability of the chip/substrate in the packaging assembly. This concerns not only the quality of the die attachment but also the thermomechanical stability of the thin or thick metallizations plated either on the chip or on the copper double bonded ceramic substrate (DBC) surfaces. Experimental studies on power electronics assemblies presented in previous frameworks have shown cohesive and interfacial ruptures within the junctions (solder, *Ag* nanoparticles, ...), the *Cu* substrate and the diamond chip [1–3]. At high loading rates, the damage originates close to the interfaces due to the formation of fragile intermetallic compounds, the presence of defects at the interfaces or the weak adhesion of certain layers of surface finishing metallization [4,5]. However, fracture mainly remains in the bulk solder at slow strain rates. In order to optimize the design of high-temperature packaging, in particular with regard to their lifetime, it is no longer sufficient to know the mechanical behavior of the constitutive materials. Indeed, interfaces and junctions are privileged zones of initiation and propagation

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Notations

Mathematical operators and symbols

$(\dot{x})$	x derivative with respect to time
(x_{ij})	second order tensor x (i and j)
x: $x = x_{ij}\, x_{ij}$	contracted product of two second order tensors x_{ij}
$x \otimes x = x_{ij}\, x_{kl}$	tensorial product of two second order tensors x_{ij}

Variables and parameters

$\boldsymbol{C}^e$	elastic stiffness tensor (MPa)
$\boldsymbol{D}, \boldsymbol{D}^p$	macroscopic strain and plastic strain rate tensors
E, v	Young modulus (MPa), Poisson ratio
f, f_0, f_c, f_F	total, initial, critical, final volume fraction of voids
f_N, s_N, ε_N	nucleation material parameters
G^c	fracture energy of the cohesive element (MPa.mm)
K	hardening coefficient (MPa)
K_h	cohesive element stiffness (MPa.mm^{-1})
n	power exponent
$\boldsymbol{n}$	normal to the Gurson yield surface (tensor)
$\vec{\boldsymbol{n}}'$	vector normal to the localization band
q_1, q_2, q_3	Gurson model parameters
t_i, t_i^0	dual stress vector of the cohesive element, maximum value of stress (MPa)
δ_i	relative displacement of the cohesive element in direction i (mm)
δ_i^0, δ_i^f	relative displacement at damage initiation and complete failure (mm)
$\delta_i^{\max}$	maximum relative displacement reached during loading (mm)
δ_{ij}	second order unit tensor
ε_0	yield strain of the matrix
$\bar{\sigma}, \bar{\varepsilon}^p$	effective stress (MPa) and plastic strain of the matrix
$\boldsymbol{\Sigma}$	macroscopic stress tensor (MPa)

of cracks in packaging; it is, therefore, important to be able to describe this overall mechanism using finite element modeling tools. The interfaces are mainly represented by cohesive laws which make it possible to evaluate the initiation and the evolution of the interfacial damage by linking the effort at the interface to its opening distance. However, the parameters of these laws are not exploitable from standard characterization tests and specific tests must then be implemented. The behavior laws of cohesive elements are usually described in terms of traction versus separation, which relates the interface relative displacement to the traction vector. Generally, the cohesive elements behave elastically until damage initiation and obey a softening behavior afterwards. The specific energy dissipated by the cohesive element can be calculated from the area under the curve. Different constitutive laws of the cohesive zone model have been proposed in the literature [6–11]. Since the shape of the function may influence the results of the simulation [12,13], it is crucial to identify a law that is suitable for capturing the interfacial fracture extension behavior of the cohesive layers. According to the nature of the material (ductile, brittle, etc.) and the type of loading considered (monotonic or cyclic loadings), the cohesive zone model can be defined. The bilinear cohesive zone model is currently the most widely used model for interfacial fracture behavior simulation due to its ability to describe different fracture modes and its availability in ABAQUS® software. Thus, it has been widely used to characterize the interfacial damage behavior in power electronic packaging [14,15]. These studies showed the performance of the bilinear cohesive zone methods for describing and predicting crack initiation and propagation at the interfaces of electronic assemblies. They also demonstrated the convergence between the numerical simulation and experimental results.

Damage can also be observed in the solder joints. Damage is mainly present in the form of micro-voids. These voids grow and nucleate during the service period leading to cracking and failure. To describe this phenomenon and for lifetime prediction, many studies have focused on continuum damage theories or fatigue criteria to describe degradation in solders. These models are mainly coupled to plasticity or viscoplasticity constitutive equations to describe the plastic deformation prior to damage initiation [16,17]. For example, some fatigue criteria such as Darveaux [18] or Manson-Coffin [19] are usually used because they are practical in numerical frameworks and give correct predictions. They can predict the lifetime of real products with complex geometry. However, the models take into account only the initial and final states of the material. The practical procedure to identify material behavior using these fatigue models is usually geometry dependent. In the general framework of continuum thermodynamics of irreversible processes, micro mechanical and phenomenological damage models are widely used [20,21]. These models are built from complex constitutive equations that require advanced integration methods. Another approach for describing fracture in solders is the maximum entropy fracture model. This type of

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