COHESIVE ZONES FOR FATIGUE DAMAGE IN SOLDER JOINTS

M. Erinç, P.J.G. Schreurs, M.G.D. Geers
Section of Materials Technology, Fac. Mech. Eng., Eindhoven University of Technology, Eindhoven, The Netherlands

ABSTRACT

Fatigue damage initiation and propagation in a solder bump, subjected to cyclic loading, is simulated using a cohesive zone methodology. Damage is assumed to occur at interfaces modeled through cohesive zones in the material, while the bulk material deforms elastoplastically. The state of damage at an interface is incorporated into the traction-displacement law of the cohesive zone by a damage variable. The gradual degradation of the interfaces and the corresponding damage accumulation throughout the cycling process is accounted for by an interfacial damage evolution law, which captures the main failure characteristics.

1 INTRODUCTION

Due to miniaturization in micro-electronics lead-frame packages are replaced by ball grid arrays (BGAs), where solder bumps connect chip and board both mechanically and electronically. Upto now the majority of solder joints is made from eutectic tin-lead alloy. The obvious toxicity of lead initiated several legislations which will result in a nearly complete ban of lead in consumer electronics in the near future. A good replacement for the tin-lead alloy is a ternary eutectic alloy of tin (Sn), silver (Ag) and copper (Cu), generally referred to as SAC.

Miniaturization leads to elevated temperatures and high current densities. Differences in coefficient of thermal expansion (CTE) between printed circuit board (PCB), electronic component (chip package) and solder material, and also between the different phases in the solder alloy, leads to considerable thermomechanical loading. Cyclic loading, due to repeated on-off switching of the device, results in the initiation and propagation of fatigue damage in the solder joints, which limits the lifetime of the components. The microstructural inhomogeneity and the stress concentrations in the solder joint contribute severely to the occurring fatigue damage. Experiments and common practice show that damage starts at and propagates along solder/pad interfaces in the material (Farooq [1]).

Due to the short design cycles of many electronic consumer devices, prototyping and testing is time consuming. Reliability of the electronic components must be assessed through numerical simulation during the design process. Regarding the small dimensions of the solder joints, the numerical models should include the microstructure. The interface damage can be modelled using a cohesive zone approach.

2 COHESIVE ZONE MODEL FOR INTERFACIAL DAMAGE

The cohesive zone method is a numerical tool to describe the mechanics of interfaces, that was initially developed to model crack initiation and growth in quasi-brittle materials. The interface behavior is specified through a relation between the relative opening displacement Δ_α and a corresponding traction T_α at the same location, with α being either the local normal (n) or tangential (t) direction in the cohesive zone mid-plane between the adjacent interfaces. For the case of monotonic loading, the cohesive traction is characterized mainly by a peak value which represents the cohesive strength and a cohesive energy (Xu [2]). When the cohesive traction reaches the peak value, a critical opening displacement is attained and the traction starts to diminish with the gradual increase of the opening displacement. This will result in the creation of two traction free surfaces, which marks the initiation of a crack or the extension of an existing one.

Under cyclic loading, the situation is rather different. If the applied traction is less than the cohesive strength, the cohesive zone will have an infinite life. Under cyclic loading, materials fail at stress levels below their static fracture strength. Following the formulation of Chaboche et al. [3], we adopt a constitutive law in which the traction is a linear function of the separation, whereas the energy dissipation associated with the gradual degradation of the material, is accounted for by the incorporation of a nonlinear damage variable D_α, which varies between zero (0) for damage-free and one (1) for completely damaged cohesive zones. The damage variable is supplemented with an evolution law based on the formulation of Roe and Siegmund [4], to account for the accumulation of damage throughout the cycling process.

$$T_\alpha = k_\alpha(1 - D_\alpha)\Delta_\alpha \qquad ; \qquad \dot{D}_\alpha = c_\alpha|\dot{\Delta}_\alpha|\,(1 - D_\alpha + r)^{\mathrm{m}}\left\langle \frac{|T_\alpha|}{1 - D_\alpha} - \sigma_{\mathrm{f}} \right\rangle \tag{1}$$

where k_α is the initial stiffness of the cohesive zone, c_α is a constant, which controls the damage accumulation, $\dot{\Delta}_\alpha$ is the rate of the relative opening of the cohesive zone, r and m are constants which control the decay of the reaction force at the final stage of damage and σ_{f} is the cohesive zone fatigue limit. Macauley brackets are used to prevent damage growth when the traction is below the fatigue limit.

A cohesive zone is modelled as a four-noded element, which may have zero initial thickness. Incorporating it in the finite element formulation requires calculating the cohesive zone stiffness matrix and internal nodal force vector. The cohesive zone element is implemented as a "user element subroutine" in the MSC.Marc finite element package [5].

3 SOLDER JOINT MODEL

Fig. 1 shows an ESEM – Environmental Scanning Electronic Microscope – picture of a solder ball made of a SAC alloy (95.5Sn-4.0Ag-0.5Cu). In the bulk material distinct shades of gray indicate colonies, consisting of β-Sn dendrites in a matrix composed of a ternary eutectic phase mixture of (Sn), Ag_3Sn and Cu_6Sn_5. In a mounted arrangement the solder is applied between copper pads. In a detailed view of the SAC/copper-pad zone a thin layer of Cu_3Sn and a layer of Cu_6Sn_5 ($\leq 5\ \mu$m) having scallop morphology can be observed. During reflow processes, depending on the cooling rate, occasional precipitation of primary Ag_3Sn occurs, nucleating at the Cu_6Sn_5 scallop tips and growing into the solder.

Monotonous loading

A tensile specimen made of two copper plates, connected by SAC solder has been loaded with a computer controlled tensile stage. Tensile testing revealed damage at the trajectory along dendrite arm tips and at the interface between colonies, as is shown in Fig. 1. In another specimen, consisting of three parallel copper plates, the connecting SAC solder is mainly loaded in shear, where global shear strain increased monotonically to a maximum $\gamma_{max} = 8.9 \times 10^{-2}$ at a rate $\dot{\gamma} = 0.33 \times 10^{-2}$ s^{-1}. As is shown in Fig. 1 void formation at the Cu/Cu_3Sn interface is observed as the primary damage mechanism under monotonic shear loading. Secondly, brittle cracking is seen in the Cu_6Sn_5 scallops with crack propagation in the direction of principle shear. Due to misalignment, bending caused delamination in some regions of the Cu_6Sn_5 scallops/solder interface. It is expected that fatigue damage localizes at these physical interfaces and cohesive zones are thus embedded at these locations.

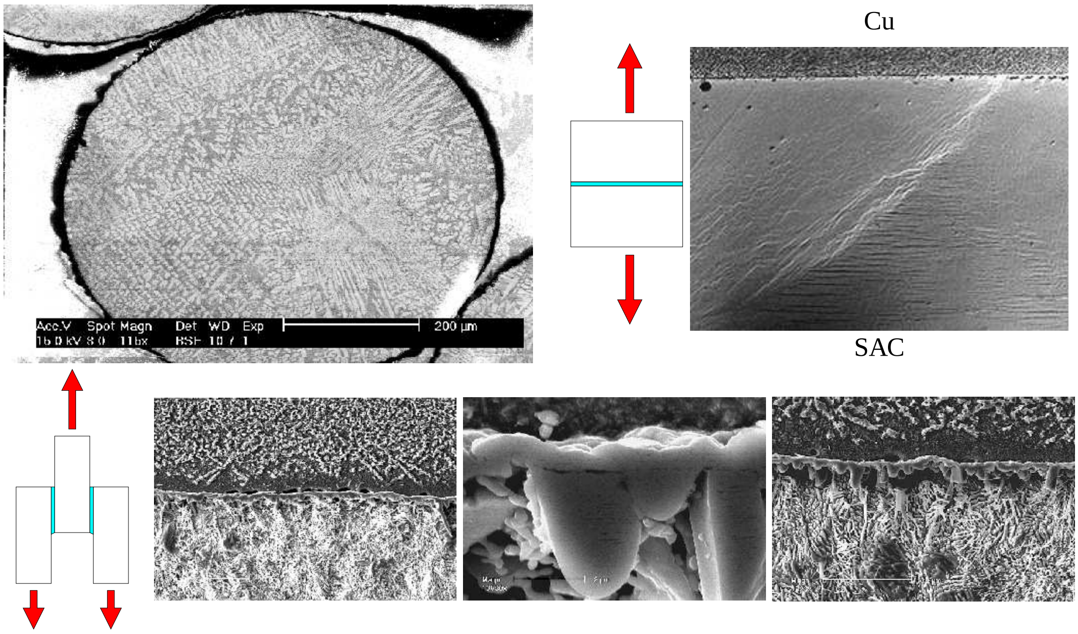

Figure 1: ESEM picture of SAC solder ball; Tensile specimen and colony boundary damage. Shear specimen and interface cracks after monotonous shear loading (bottom).

Geometry

A single solder bump is modeled in plane strain, which is an approximation of the actual three-dimensional problem. The height of the bump is 1 mm as is the width of the pads. Cohesive zones with a thickness of $\pm 10\mu$m are located between colonies. The Cu_3Sn layer is not modeled, not only due to its small thickness but also because shear damage is not observed in this layer. The Cu_6Sn_5 layer has a thickness of 3 μm. Cohesive zones with a thickness of 0.1 μm are placed between this layer and the adjacent SAC and copper pad.

Material parameters

Indentation tests were used to measure the Young's modulus (E) of bulk material and intermetallic compounds, according to the procedure described by Oliver and Pharr [6]. Tests were done with a MTS Nano-Indenter XP, equipped with a Berkovich indenter. Poisson's ratios (ν) of the components are taken from literature. With the Young's modulus known from direct measurement, the initial yield stress (σ_{v0}) and the linear hardening coefficient (H) of these materials could be determined by a hybrid approach, where the indentation tests were simulated with FEM and comparison of experimental and numerical load-indentation data provided the material parameters. The material parameters are listed in table 1. Cohesive zones are given a high value for the initial stiffness $k_\alpha = 10^9$ MPa/mm, which is estimated from their initial thickness. The initial stiffness must be sufficiently high, compared to the continuum stiffness, such that, in the absence of damage, the cohesive zones artificial enhancement of the overall compliance is negligible. For the current model, it has been verified that using higher values for the initial stiffness, leads to identical reaction forces at the first cycle. Damage growth parameters for cyclic loading are not experimentally determined yet. Most non-ferrous alloys have no fatigue limit, so $\sigma_f = 0$ Pa. Parameter values for r and m are based on numerical analyses of simple tensile and shear tests. For each cohesive zone we take : $r = 10^{-3}$

			SAC	Cu	Cu_6Sn_5	$cz_{1/4}$	$cz_{2/3}$	colonies
Young's modulus	E	GPa	26.2	128.5	85.6			
Poisson's ratio	ν	-	0.35	0.35	0.2			
initial yield stress	σ_{v0}	MPa	22.0	175.0	100.0			
hardening coefficient	H	GPa	0.83	4.15	3.70			
cohesive zone par.	c_n	mm/N				c	$5c$	$1.5c$
cohesive zone par.	c_t	mm/N				$5c$	c	$1.5c$

Table 1: Material and cohesive zone parameters for solder ball components. $cz_{1/4}$ = Cu/Cu_3Sn ; $cz_{2/3}$ = Cu_6Sn_5/SAC.

and $m = 3$. Values for c_n and c_t are expressed in a constant c, which is taken rather arbitrarily and extracted from numerical experiments. The distinction between different cohesive zones is made by assigning different values for these coefficients. Values are listed in table 1.

Cyclic loading

Cyclic loading is applied by prescribing a sinusoidal x-displacement in the top-right node of the top boundary. The y-displacement of this node is always suppressed. The y-displacement of all other points on the top boundary is either suppressed (TS) or free (TF). The prescribed sinusoidal x-displacement has an amplitude of 0.01 mm, which results in a maximum applied shear strain $\gamma_{\max} = 10^{-2}$. The lower boundary is fixed.

4 SOLDER JOINT FATIGUE DAMAGE

Fig. 2 shows the maximum deformation after 500 cycles for boundary conditions TS and TF, respectively. Displacements are scaled up 10 times to emphasize the deformation in the cohesive zones. Damage in the cohesive zones is also indicated with a color scale. The SAC/pad interfaces lose coherency almost completely. As damage progresses, the overall stiffness of the bump diminishes and the load required to attain the same strain level decreases. Fig. 3 shows the maximum and minimum values of the load during the subsequent cycles for the different boundary conditions. The discontinuous changes in the load for TS indicate the total loss of shear strength of the Cu/Cu_6Sn_5 interface zone at lower and upper pad, respectively.

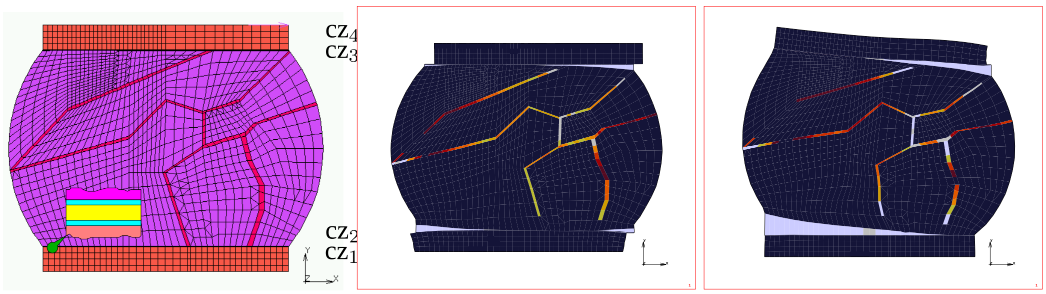

Figure 2: Left: bump element mesh. Right: deformation (10×) for boundary conditions TS and TF.

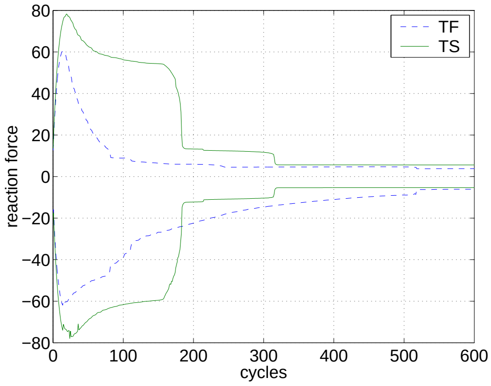

Figure 3: Load versus the number of cycles for boundary conditions TS and TF.

5 CONCLUDING REMARKS

The cohesive zone approach seems promising in modeling fatigue damage in solder alloys. Gradual degradation of interfaces can be incorporated. Fatigue damage propagation paths emerge naturally during cyclic loading. The boundary conditions have a big influence, because they determine the loading of the cohesive zones.

In the near future cohesive zone parameters will be determined in an indirect manner. More realistic modeling of bulk material behaviour must incorporate time and temperature dependency. The detailed simulation of each individual cycle is time consuming. A major gain in the computational effort must be obtained by the use of a time homogenization technique.

5 REFERENCES

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Acknowledgements This research is supported by the Technology Foundation STW, applied science division of NWO and the technology programme of the Ministry of Economic Affairs.