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A general methodology for calculating mixed mode stress intensity factors and fracture toughness of solder joints with interfacial cracks

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ABSTRACT

Solder joints in electronic packages undergo thermo-mechanical cycling, resulting in nucleation of micro-cracks, especially at the solder/bond-pad interface, which may lead to fracture of the joints. The fracture toughness of a solder joint depends on material properties, process conditions and service history, as well as strain rate and mode-mixity. This paper reports on a methodology for determining the mixed-mode fracture toughness of solder joints with an interfacial starter-crack, using a modified compact mixed mode (CMM) specimen containing an adhesive joint. Expressions for stress intensity factor (K) and strain energy release rate (G) are developed, using a combination of experiments and finite element (FE) analysis. In this methodology, crack length dependent geometry factors to convert for the modified CMM sample are first obtained via the crack-tip opening displacement (CTOD)-based linear extrapolation method to calculate the under far-field mode I and II conditions (f_{1a} and f_{2a}), (ii) generation of a master-plot to determine a_c, and (iii) computation of K and G to analyze the fracture behavior of joints. The developed methodology was verified using J-integral calculations, and was also used to calculate experimental fracture toughness values of a few lead-free solder-Cu joints.

1. Introduction

Most handheld electronic devices undergo thermo-mechanical cycling during service and therefore, tiny low-cycle fatigue cracks form early in the service life of the solder joints. These pre-existing cracks may propagate under a combination of tensile and shear loading (i.e. mixed-mode loading) when the package sustains an impact during a drop. In addition, the scale of plasticity at the crack tip is not the same for solder joints processed with different solder composition or joint-reflow conditions or the post-reflow thermo-mechanical excursions, which results in varied effective crack growth as well as fracture toughness [1–5]. Thus, it is necessary to develop a general methodology to evaluate the fracture resistance capability of solder joints after duly addressing the varied effective crack growth.

Critical stress intensity factor, K_C, and strain energy release rate, G_C, are the most common parameters used to characterize the fracture toughness of materials. Unlike a crack embedded in a homogeneous body (Fig. 1a), stress-field

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Nomenclature

a	crack length (m)
C	compliance (m/N)
E	Young's modulus (MPa)
E'	plane strain Young's modulus (MPa)
f	geometry factor (dimensionless)
G	strain energy release rate (J/m^2)
H	substrate height (m)
J	J integral value (J/m^2)
k	tangent modulus (MPa)
K	stress intensity factor (MPa m$^{0.5}$)
K'	normalized stress intensity factor (MPa m$^{0.5}$)
l	characteristic length (m)
P	force (N)
r	distance from the crack tip (μm)
s	path along a J-integral contour (m)
t	thickness of the specimen (m)
$\vec{T}$	stress vector acting on a contour (MPa)
$\vec{u}$	displacement vector (m)
u	node displacement of finite element model after loading (m)
UX	displacement in direction x, applied as boundary condition in the finite element model (m)
UY	displacement in direction y, applied as boundary condition in the finite element model (m)
w	strain energy density (J/m^3)
W	width of the joint (mm)

Greek symbols

α	Dundurs parameters (dimensionless)
β	Dundurs parameters (dimensionless)
δ	relative crack-tip opening displacement (m)
ε	Dundurs parameters (dimensionless)
$\dot{\varepsilon}_{strain}$	strain rate (s^{-1})
ϕ	loading angle (°)
Γ	integral path for J-integral (m)
μ	shear modulus (MPa)
v	Poisson's ratio (dimensionless)
θ	angle originating from the crack tip of finite element model (°)
σ	normal stress (MPa)
τ	shear stress (MPa)
ψ	mode mixity (°)

Subscripts

0	initial value
1	material 1 or node 1
2	materials 2 or node 2
1a	mode I component for interfacial crack
2a	mode II component for interfacial crack
a	combined effect of adhesive and substrate
c	critical value
I	mode I component
x	x direction of the coordinate at the crack tip
y	y direction of the coordinate at the crack tip

heterogeneities in the presence of interfacial cracks (Fig. 1b and c) are also caused by discontinuity in the elastic properties of the two adjoining materials composing the interface. This elastic (or materials) mismatch is contained in the three Dundurs parameters, namely ε, α and β, which are given as follows [6]:

$$\varepsilon = \frac{1}{2\pi} \ln \frac{1-\beta}{1+\beta} \tag{1a}$$

$$\alpha = (E'_1 - E'_2)/(E'_1 + E'_2) \tag{1b}$$