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An experimental setup for characterizing subcritical debonding of materials interface under mixed mode fatigue loading

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A B S T R A C T

A mixed mode bending experimental setup was developed for quantifying the subcritical debonding growth behavior for materials interfaces under a full spectrum of loading mode mixity. In the experimental system, the control program calculates and adjusts the cyclic bending forces to maintain a constant phase angle at the prescribed value. The relationship between the subcritical crack growth rate and the applied strain energy release rate range is obtained by post-processing the experimental results with analytical formulas. As a preliminary application example, a phase-angle dependent power-law model was constructed for the subcritical debonding growth rate of the Al-epoxy interface. It was observed that both the logarithm of the scaling constant and the power-law exponents of the subcritical debonding growth model exhibit linear relationships with the phase angle.

1. Introduction

Interconnect structures used in modern electronics such as silicon-level metal/ceramic thin film stacks and glass-fiber laminate boards consist of multi-layered arrangements of electrical conductors and insulators. Due to the dissimilar thermomechanical properties across the materials interface, high stress would develop in the layered structure during fabrication or in-service conditions. Furthermore, the lack of metallic or covalent bonds between the dissimilar materials make the interface susceptible to debonding. Consequently, interface delamination is one of the primary root causes of reliability failures for interconnect. A favorable methodology for assessing the reliability associated to interface delamination is the fracture mechanics approach. This approach involves analyzing the debonding driving forces locally at the interface crack tip and comparing them to the interfacial adhesion properties for reliability life estimation. From the perspective of fracture mechanics, the driving forces of debonding growth in interconnect and package structures include the strain energy release rate and stress intensity factors. Evaluations of these parameters were mainly through numerical finite element (FE) procedures, e.g., [1–3]. The corresponding debonding resistance locally at the interface crack tip can be characterized by the critical strain energy release rate for the onset of a spontaneous crack growth; and by a debonding growth rate model when the materials interface is experiencing subcritical creep or fatigue loads.

It is well known that the critical strain energy release rate of a bimaterial interface crack is strongly dependent on the loading mode mixity [4]. The critical strain energy release rate is the lowest when the applied loading is of Mode-I/perpendicular to the interface crack faces, and is increasing as the contribution of Mode-II/shear loading increases [5]. Because the debonding parameter measured by testing under Mode-I condition is closely related to the intrinsic adhesion energy, it could serve as a conservative estimation of the interface reliability. A popular Mode-I experimental setup for characterizing interfacial adhesion is the double cantilever beam (DCB) test [6]. Several experimental studies had been conducted by using the DCB to characterize interfacial adhesion in microelectronics applications: Guzek et al. [7] studied the interfaces of silica-filled polymers and Ni or Cu, and characterized the fatigue crack propagation behaviors for these interfaces; Snodgrass et al. [8] investigated the subcritical crack growth behavior on the interface of benzocyclobutene (BCB) and silica by using both DCB and mixed-mode four-point bending tests; McAdams and Pearson [9] measured the critical strain energy release rate for several underfill-polyimide interfaces by using asymmetric DCB test setup; Zhu et al. [10] measured the critical strain energy release rate and the subcritical debonding growth response of the SiN-polyimide interface by using DCB.

For interface crack under mixed-mode loading, the ASTM mixed mode bending (MMB) test [11] devised by Reeder and Crews [12] allows measuring the critical strain energy release rate of interface crack under a wide range of mode mixity, and has been applied to study structural composite laminates [13–16] and microelectronic structures

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Nomenclature

a	crack length
B, n	constants of the fatigue debonding growth rate model
b	width of the beam
c	length of the unsplit portion of the beam
E_1, E_2	elastic moduli shear moduli the unidirectional glass-fiber-reinforced plastic
E_F, E_T	equivalent elastic moduli of the beam in the axial and transverse directions
$E_\xi^{(k)}$,$G_{\xi\eta}^{(k)}$	elastic and shear moduli of the k-th-layer material in the composite split beam
F_1, F_2	end loads on the split beam for the MMB problem
G, G_{max}, G_{min}	strain energy release rate
G_I, G_{II}	strain energy release rate for the Mode-I and Mode-II problems
G_{12}, G_{13}	shear moduli of the unidirectional glass-fiber-reinforced plastic
h	half-thickness of the beam
h_k	thickness of the k-th layer in the composite split beam
I	area moment of inertia of the split beam
K_I, K_{II}, K_{III}	Mode-I, -II and -III stress intensity factors
k_s	spring constant of the spring in the beam-on-elastic support model
L_{11}, L_{22}	(1, 1) and (2, 2) entries of the Barnett-Lothe tensor, $\boldsymbol{L}$
l_1, l_2	distances between the transverse loading points on the beam
m	the number of the layer where the neutral axis of the composite split beam resides in
N	number of fatigue cycles
P_1, P_2	end loads on the split beam for the DCB and ENF problems
r	polar coordinate with origin at the crack tip
$\hat{r}$	characteristic length for normalization of stress intensity factor
v_I, v_{II}	transverse deflections of the beam in the DCB and ENF problems
S_1, S_2, S_3	parameters of the composite split beam
α_1, α_2	parameters of the composite split beam
β, χ	parameters used in the formulas for crack length calculation
γ_1, γ_2	parameters used in the formulas for the end-load ratio calculation
Δu_x, Δu_y, Δu_z	crack opening displacements
δ_I	crack opening displacement of the DCB problem
δ_{II}	end-point deflection of the ENF problem
$\varepsilon_\alpha (\alpha = 1,2,3)$	bimaterial constants of the interface crack problem
κ	parameter in the short-beam correction for the transverse deflections of the split beam
Λ	bimaterial eigenvector matrix of the interface crack problem
λ	parameter in the beam-on-elastic support problem
ν_{12}, ν_{13}, ν_{23}	poisson's ratios of the unidirectional glass-fiber-reinforced plastic
ξ, η	local coordinates for the composite split beam
σ_{xy}, σ_{yy}, σ_{yz}	stresses
ψ	phase angle

[5,17]. The MMB test specimen is a beam containing an edge pre-crack/delamination at the mid-plane. Tabs are adhered to the split end of the beam for applying transverse loads. With the application of a single transverse load through a lever-and-fulcrum fixture, the test specimen is loaded simultaneously under Mode-I double cantilever bending and Mode-II end notched flexure (ENF) conditions. The critical strain energy release rate is obtained by substituting the experimentally measured crack length and the critical debonding load into a numerically augmented analytical formula [11]. By using the MMB setup, Ducept et al. [13] measured the mode-mixity dependent critical strain energy release rate for the glass-epoxy interface in composites, Kim and Mayer [14] studied the delamination fracture toughness of a carbon/epoxy laminates, Samborsky et al. [15] investigated the adhesive joints of fiberglass laminates used for wind turbine blades, Moslemian and Berggreen [16] studied the interfaces of polyvinyl chloride foam core and glass/polyester face sheets, Kolluri et al. [5] and Sadeghinia et al. [17] investigated the adhesion between the Cu leadframe and epoxy molding compound. In addition to the standard ASTM MMB apparatus, alternative loading jigs including link-and-lever [18] and arm-and-wire [19] setups were developed for applying the uneven bending moments. Aside from the MMB test, there are some alternative but less general approaches for measuring the interface adhesion under mixed mode loading, such as the four-point bending test [8], which has limited range of mode-mixity, and the stressed-Cr-super-layer enabled thin film decohesion test [20], which requires specimen compatibility to the super layer process.

While the MMB test has been successfully applied for measuring the critical strain energy release rate under a prescribed loading mode mixity, it is less suited for characterizing subcritical debonding growth because the loading mode mixity of the interface crack changes as the debonding length increases. As an example, the numerical finite element solutions of a split composite beam as shown in Fig. 1 under MMB are given in Figs. 2 and 3 [21]. It can be seen from Fig. 2 that the end-load ratio, F_1/F_2, should be varied continuously from 5.64 to 3.82 to ensure a constant mode mixity or phase angle of -30° during the debonding growth from 5 mm to 30 mm. On the other hand, the phase angle would decrease from -20° to -23° if F_1/F_2 is kept constant at 2.5 (Fig. 3). The change in phase angle corresponds to 17% increase in Mode-II contribution. While the change is much less if the crack length stays above 20 mm, a subcritical debonding experiment starting from a larger initial crack may not have sufficient propagation distance for collecting subcritical debonding growth response, in particularly for the microelectronic applications where specimen sizes are typically limited. Therefore, a revised loading scheme is required for implementing the

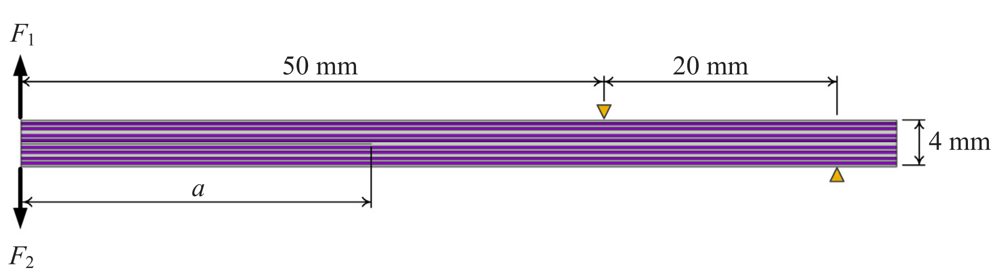

Fig. 1. A split laminated composite beam under mixed-mode bending [21].