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Some Effects of Specimen and Loading Variables on the Fracture Toughness of Epoxy-to-Substrate Interfaces

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The nucleation and growth of cracks at critical interfaces can degrade electrical and mechanical performance of electronic assemblies. Sandia National Laboratories is working to develop a fracture mechanics-based approach for assessing the reliability of components containing interfaces and subjected to thermal/mechanical fatigue. Models are being developed to predict the nucleation of a crack-like flaw in the vicinity of an interface, the path of crack propagation (along interface or into substrate), and the conditions for crack propagation. In addition, interfacial fracture toughness data are being generated to support model development. This paper summarizes an experimental study aimed at measuring the fracture toughness of epoxy-to-substrate interfaces that are representative of those found in bonded and encapsulated electronic components.

One measure of the resistance to crack growth is interfacial toughness G_c. An Asymmetric Double Cantilever Beam (ADCB) specimen of the type shown in Fig. 1 was used to measure G_c.

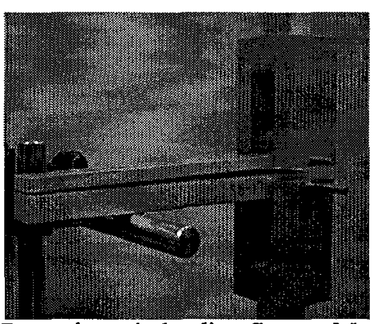

Fig. 1. ADCB specimen in loading fixture. Metal substrates (2:1 thickness ratio) have dimensions of thickness = 4.8 & 9.6 mm, width = 12.7 mm, and length = 120 mm. Epoxy layer thickness = ~ 0.5 mm or 1.0 mm.

Two metal substrates are bonded together with an epoxy interlayer and a starter crack is introduced at the thinner substrate/epoxy interface. This starter crack can then be extended in quasi-static, tensile, load/unload tests. A typical load versus load-point deflection response curve is shown in Fig. 2. This curve is used to determine multiple values of interfacial fracture toughness G_c from a single specimen. Fig. 3 shows that over a large range of crack lengths, consistent values of G_c can be obtained with single ADCB specimen.

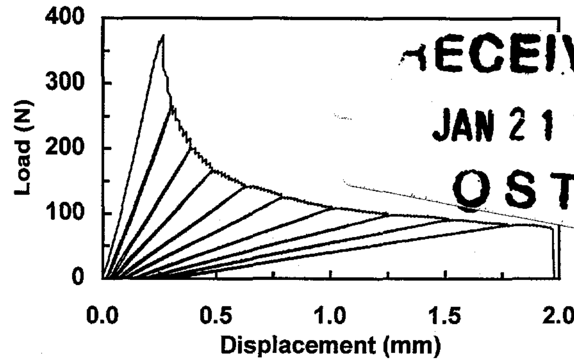

Fig. 2. Typical load/unload vs. displacement response of ADCB specimen with 303 stainless steel substrates having 5 micron rms surface roughness.

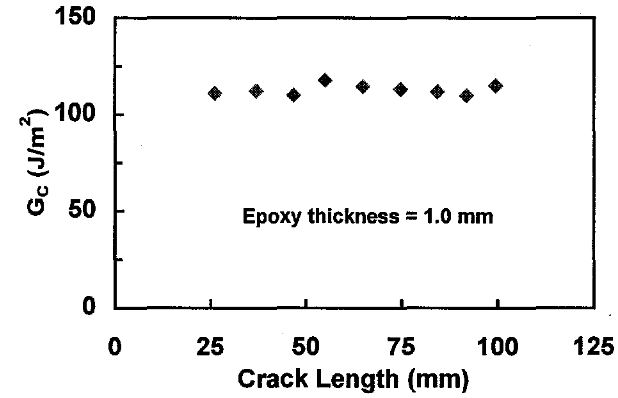

Fig. 3. Interfacial fracture toughness G_c vs. crack length of stainless steel/epoxy ADCB specimen having 5 micron rms surface roughness.

Once specimen fabrication, test procedure and data reduction techniques were in place, the ADCB specimen was used to probe the effects of material and specimen variables on interfacial fracture toughness. Variables included epoxy type and thickness, substrate material and surface roughness, and cleaning processes for the substrates. Table 1 lists the combination of variables tested along with resultant G_c data. G_c values are plotted as a function of bond line thickness in Figs. 4-5 for different test variables. Data in Table 1 and Figs.3-5 suggest the following:

Effect of bond thickness- There are relatively small variations in measured toughness when the bond thickness is varied from ~ 0.5 mm to ~1.0 mm (Table 1 & Fig. 4).

Effect of surface roughness- G_c is a strong function of surface roughness, increasing about a factor or 5 as the surface roughness increases 1 to 5 microns rms (Fig. 4).

Effect of cleaner type- Fig. 4 shows that the measured toughness of samples with a Brulin cleaned aluminum surface is significantly greater than that for a TCE cleaned aluminum surface

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Table 1. Test Variables and Experimental Results

Interface[1]	Roughness rms (microns)	Epoxy Nominal Thickness (mm)	Cleaning Process[2]	G_c (J/m^2)
SS / Epoxy 1	5	0.5	Passivation	**118**
	5	1	Passivation	**115**
Al / Epoxy 1	1	0.5	Brulin	**23**
	1	1	Brulin	**31**
	5	0.5	Brulin	**132**
	5	1	Brulin	**115**
	1	0.5	TCE	**15**
	1	1	TCE	**15**
	5	0.5	TCE	**80**
	5	1	TCE	**89**
Al / Epoxy 2	5	0.5	Brulin	**97**
	5	1	Brulin	**104**
Al / Epoxy 3	5	0.5	Brulin	**116**
	5	1	Brulin	**106**
Silicon / Epoxy 1	Polished wafer	0.5	Alcohol	**20**

[1] SS = 303 stainless steel, Al = 6061 T6 aluminum, Epoxy 1 = Shell Epon 828 resin with Huntsman T403 hardener using a 100/43 weight ratio, Epoxy 2 = Epon 828 resin with diethanolamine (DEA), hardener using a 100/12 weight ratio, and Epoxy 3 = Epoxy 2 with a beta-eucryptite filler with a 100/12/185 weight ratio.

[2] Passivation = process with nitric acid solution, Brulin = Brulin 815GD aqueous cleaner, and TCE = trichloroethylene solvent.

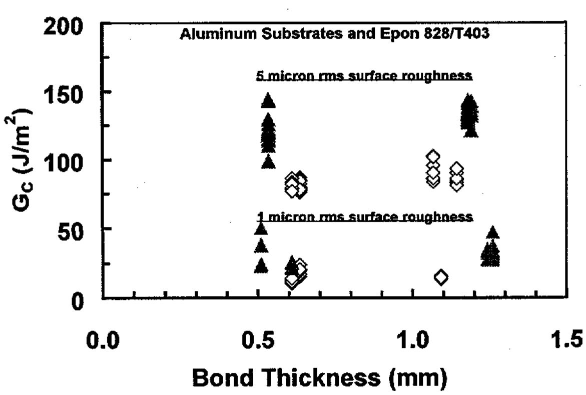

Fig. 4. Effects of bond thickness, surface roughness, and cleaner type on the interfacial fracture toughness G_c of aluminum/epoxy 1 interfaces. (Solid symbols = Brulin cleaner and open symbols = TCE cleaner.)

(~50% greater). This is possibly due to some micro etching of the aluminum by the Brulin cleaner.

Effect of epoxy type & filler in epoxy- For aluminum substrates of 5 micron roughness cleaned with Brulin, the toughness of an interface with epoxy 1 ($G_c \approx 122$ J/m^2) was about 20% greater than an epoxy 2 ($G_c \approx 100$ J/m^2) interface (Table 1). Addition of beta eucryptite filler to epoxy 2 did not significantly change G_c (Fig. 5).

Effect of substrate material- Stainless steel and aluminum substrates with 5 micron roughness have similar values of G_c (115 to 130 J/m^2, Table1).

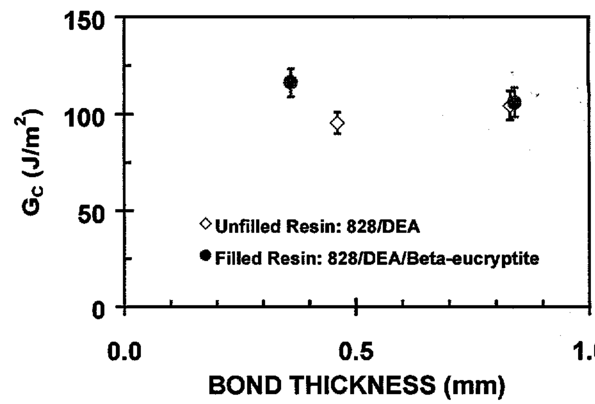

Fig. 5. Effects of bond thickness and beta eucryptite filler on the interfacial fracture toughness G_c of aluminum/epoxy 2 & 3 interfaces. The symbols are average values and the bars are one standard deviation. (Surface roughness = 5 micron rms).

The DCB specimen was modified to accommodate a thin, brittle silicon wafer material by secondarily bonding the silicon to an aluminum substrate. The toughness of the silicon/epoxy 1 interface is 20 J/m^2. This is similar to the toughness of a 1 micron al/epoxy interface.

Cyclic fatigue tests were performed to measure the number of cycles N required to extend the interface crack a distance of 1 mm. The applied energy release rate/energy release rate versus N data in Fig. 6 suggest that ~35% increase of G/G_c shortens the fatigue life by one decade. Note also that the fatigue responses are similar for the filled and unfilled epoxies.

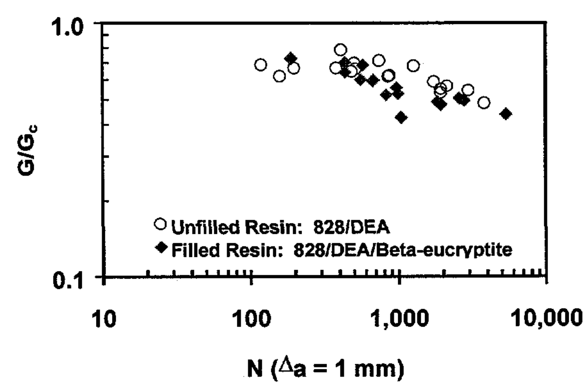

Fig. 6. Number of cycles N to propagate an interfacial crack 1 mm as a function of applied strain energy level G/G_c. Aluminum/epoxy 2 & 3 interfaces. (Surface roughness = 5 micron rms).

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