SAND2019-15016C

Interfacial Toughness: Effect of Surface Roughness and Test Temperature

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Introduction

Interfacial toughness quantifies resistance to crack growth along an interface [1] and in this investigation the toughness of an epoxy/aluminum interfaces was studied. This material property can be used as a measure of bond quality as well as a primary input in finite element simulations of crack growth in adhesively bonded and encapsulated structures. Interfacial toughness depends on many variables including test temperature, rate of loading, interfacial surface roughness and interfacial chemistry. It also depends on the level of crack-tip energy dissipation (e.g., yielding) that occurs in the adjacent bulk materials. The relationship between toughness values and the parameters that control toughness is in general unknown and must be determined through extensive testing. Here we identify a simple relationship that connects interfacial toughness, surface roughness, and polymer yield strength (which is linearly dependent on test temperature).

Experimental

An adhesively bonded Asymmetric Double Cantilever Beam (ADCB) specimen was used to measure interfacial toughness. The ADCB specimen used in this study bonds 4.7 and 8.9 mm thick 6061-T6 aluminum beams together with a nominally 0.5 mm-thick epoxy layer. The ADCB specimen is pinned into a load train that utilizes a chain linkage and is loaded by pulling the ends apart at a crosshead displacement rate of 0.02 mm/s to propagate a crack along the interface with the thinner beam (Fig. 1). The crack grows stably with increasing end displacement allowing several toughness measurements to be made while testing a single specimen. Crack length is inferred from specimen compliance, and the specimen is unloaded after each toughness measurement to establish the crack length when reloading to make another toughness measurement. The calibration used to determine toughness values from the 1) inferred crack length and 2) the measured load at the initiation of crack growth is based on published results for a homogeneous ADCB specimen that ignores the compliance of the thin adhesive bond [2]. These results for a homogeneous specimen can be converted to those applicable to a sandwich test specimen with a middle layer (e.g., adhesive bond) that is thin relative to other dimensions [3]. Using this conversion, the sandwich specimen employed in this study has a crack-tip mode-mixity $\psi_{r=0.01\ \mathrm{mm}}$ of about -20°.

The aluminum interface that was tested was either highly polished (with a measured root mean square surface roughness $R_q \approx 0.1$ μm), slightly roughened ($R_q \approx 1$ μm), or grit blasted ($R_q \approx 6$ μm). Prior to bonding, the 6061-T6 aluminum surfaces were cleaned by sonicating in deionized water for 10 minutes, immediately removing and wiping clean with isopropyl alcohol, wiping again with isopropyl alcohol, and finally drying with nitrogen. The epoxy used to fabricate the adhesively bonded ADCB was composed of EPON® Resin 828 cured with diethanolamine using a 100:12 pbw mix ratio and a 70°C cure temperature. This epoxy, referred to as 828/DEA, has a T_g of 70° C. Specimens were tested at room temperature (RT), -20 °C, or -60 °C.

Compression tests of epoxy cylinders were used to determine how the epoxy's yield strength depends on test temperature as well as stress-strain response to large strains (≈ 40%). The epoxy specimens were cured in the same manner as used to fabricate the ADCB specimens. The compression specimens were loaded at strain rate of ≈ 0.001/s and tested at RT, -20°C, or -60°C.

Results

Figure 2 plots the measured interfacial toughness Γ of the 828/DEA-to-aluminum interface as a function of test temperature and surface roughness. The measured interfacial toughness increased ≈ 60 % when test temperature was decreased from RT to -60C. There was a factor of ≈ 14 increase in toughness when R_q was increased from 0.1 μm to 6 μm. Note that compression tests of the 828/DEA epoxy showed that the epoxy's yield strength varies linearly with temperature with a yield strength of 94 MPa at room temperature and a yield strength of 176 MPa at -60 °C. Consequently, interfacial toughness can also be expressed as a function of surface roughness and epoxy yield strength.

A simple model that relates Γ, surface roughness, and epoxy yield strength has been developed. We find that interface toughness scales as the product of the temperature dependent epoxy yield strength σ_y and a length scale that characterizes surface roughness (here we use R_q). The proposed scaling is based upon dimensional considerations of a model problem that assumes that the characteristic length scale of both the roughness and the crack-tip yield

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zone is small relative to the region dominated by the linear elastic asymptotic crack-tip stress field. Furthermore, as observed in our compression tests, the polymer is assumed to rapidly harden at large strains, and unlike yield strength, the strain level associated with the onset of rapid hardening is weak function of test temperature. The proposed relationship is validated by our measurements for an aluminum/epoxy interface (Figure 3). We anticipate the proposed relationship is a starting point for reducing the amount of testing required to quantify the dependence on interfacial toughness of material and environmental conditions.

Acknowledgements

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References

1. Hutchinson, J. W. and Z. Suo (1992), Advances in Applied Mechanics. J. W. Hutchinson and T. Y. Wu, Academic Press. **29:** 63-191.
2. Bao, G., S. Ho, Z. Suo and B. Fan (1992), International Journal of Solids and Structures **29**: 1105-1116.
3. Suo, Z. and J. W. Hutchinson (1989), Materials Science and Engineering **A107**: 135-143.

Figures

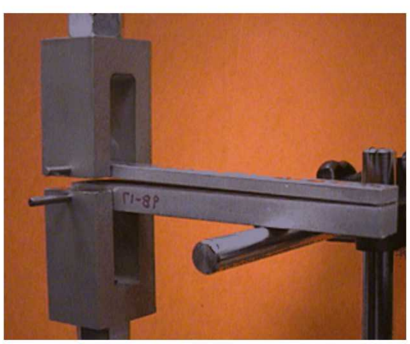

Figure 1. Adhesively bonded, Asymmetric Double Cantilever Beam (ADCB) specimen pinned to load train.

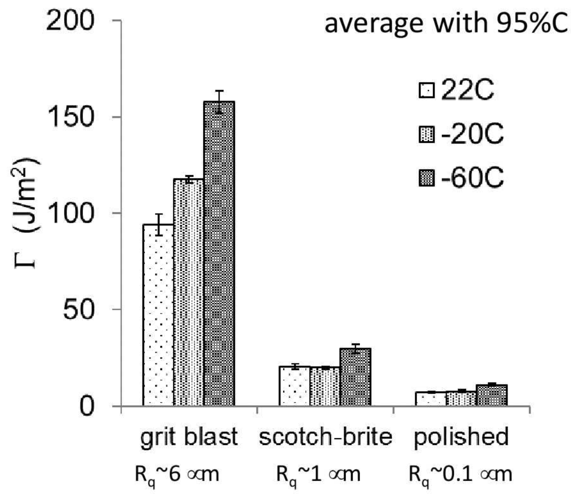

Figure 2. Measured temperature and surface roughness dependent interfacial toughness of the 828/DEA-to-aluminum interface ($\psi_{r=0.010\ mm} = -20^o$)

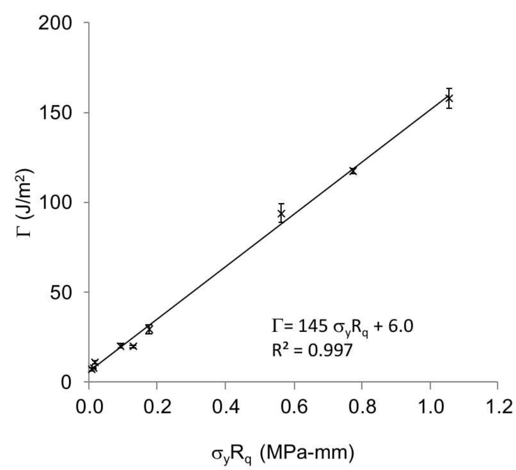

Figure 3. Measured interfacial toughness vs. the compound parameter $\sigma_y R_q$.