SAND2013-10717C

Role of Residual Stress on the Strength of Adhesive Joints

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Introduction

The reliable operation of many electrical, mechanical and optical assemblies depends on the integrity of adhesively bonded joints. The strength of an adhesive joint is determined by a number of factors which include: the cohesive strength of the adherend and adhesive materials that make up the joint, the interfacial bonding strength between adherend and adhesive, the presence of residual stress in the adhesive, and the stress distribution in the joint during mechanical loading. The focus of this work is on one of these contributing factors, the residual stress built up in a polymer adhesive during preparation of the joint. The ability to accurately predict the strength of an adhesive joint relies on understanding the role of residual stress, which has not been fully resolved.

Failure of an adhesive joint occurs when and where the local stress exceeds the local strength. Assuming the joint is designed such that weak boundary layers do not exist, then failure will take place in the weakest phase (adherend or adhesive) of the joint. When considering a polymer adhesive bonding metal adherends, the adhesive is typically the weak-link. Even given this simplification, the relation between the strength of an adhesive joint and the strength of the weakest material is complex. The factors at play in this relation are illustrated in equation 1,[1]

$$f_m = \frac{1}{\alpha}\left(\frac{\xi}{\beta} - s\right), \qquad (1)$$

where f_m is the breaking stress of the joint, ξ is the molecular cohesion of the weakest-link, β takes into account weakening of the material due to inherent flaws, s describes stresses built up in the adhesive due to factors such as confined cure and temperature history (where thermal expansion mismatches between adherend and adhesive lead to differential strains between materials as temperature changes), and α accounts for a non-uniform stress distribution in the adhesive during mechanical loading of the joint. Thus, even assuming ξ/β to be equivalent between the bulk adhesive and the adhesive in a joint, the factors α and s, and how these factors vary with joint design, processing history, etc, must be understood.

The napkin-ring (NR) joint geometry [see Figure 1 (a) and (b)] provides an opportunity to focus on the effect of residual stress on joint strength. The NR has a uniform strain upon torsional loading, both across the width of the annulus and through the thickness of the joint, up until failure [see Figure 1(c)].

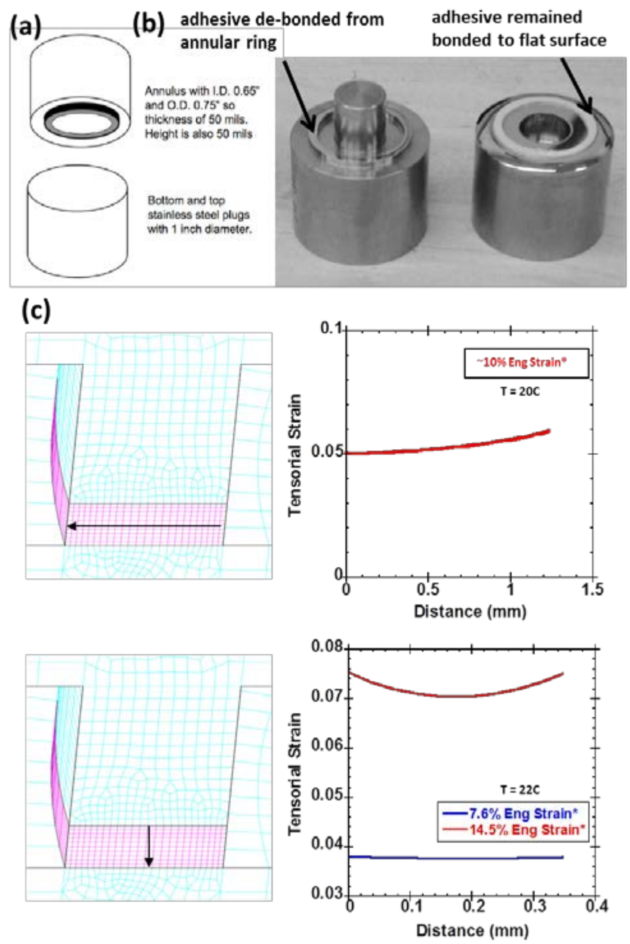

Figure 1. Schematic of napkin-ring geometry (a), image of NR after failure (b) and stress distributions in the joint during loading (c). In (c) the cyan regions represent the adherends and the pink represents the adhesive. The arrows illustrate the trace for which local strains are plotted to the right, with the point of the arrow at the largest distance.

This implies $\alpha \sim 1$ and poses the possibility of resolving the effect of s on f_m. Residual stress in the adhesive can be changed systematically by multiple means, including: (1) decreasing bond thickness (increasing the bond aspect ratio) of the joint, (2) constraining bond gap during processing and (3) applying combined axial and torsion loads to the joint. Coupled with finite element analysis of the local stress distribution in the joint, tests of NR joint strength as a function of these variables may be able to resolve the influences of residual stress in the adhesive on both the joint failure load and the mechanism of failure.

Experimental

The napkin-ring adhesive joints used were machined from 304 stainless steel with the dimensions shown in Figure 1 (a). Adherends were bonded together with the annulus as the upper surface, and the bond line (0.5 mm) was set by a steel dowel adjusted with a screw that could be backed off after cure to allow frictionless testing. Before testing, all joints were annealed above T_g for 30 minutes and then cooled at 0.5C/min to room temperature. Debonding occurred preferentially at the annulus [Figure 1 (b)] due to the small meniscus formed at the lower, flat plug surface thereby creating a somewhat larger bonding area. All joint torsional loading is completed as a controlled displacement torsional ramp (~2.5% engineering shear strain per sec) on one of two instruments: (1) MTS 858 Mini BionixII servohydraulic axial/torsional test frame or (2) Instron 55MT torsional test frame augmented with a rotary variable differential transformer (RVDT) to quantitatively monitor relative torsional displacement between the two adherends. When combined axial and torsion loading is required, tests must be performed on the MTS 858 Mini BionixII servohydraulic axial/torsional test frame.

Two thermosetting epoxy materials have been used, which we will refer to as 828/DEA and 828/T403. The 828/DEA material is a mixture of EPON® Resin 828 (Momentive), a diglycidyl ether of bisphenol A, and diethanolamine (Fisher Scientific). The materials are mixed at a ratio of 100:12 parts by weight 828:DEA and cured at T=71C for 24 hours. The resulting T_g of the cured material is ~70C. Material property characterization results of this material are available electronically.[2] The 828/T403 is again a mixture of EPON® Resin 828 (Momentive), but this time with Jeffamine ® T-403 polyetheramine (Huntsman). In this case the T403 is a trifunctional primary amine having an average molecular weight of 440 g/mol. The materials are mixed at a ratio of 100:43 parts by weight 828:T403, essentially a stoichiometric pairing of the epoxide and amine, and cured at T=80C for 24 hours. The resulting T_g of the material is ~80C.

Computational analyses of the experiments use the SPEC non-linear viscoelastic model[3] to represent the polymer adhesive.

Napkin-Ring Failure and Role of Residual Stress

The temperature dependence of the strength of the NR joint (as depicted in Figure 1) is given for two adhesives in Figure 2.

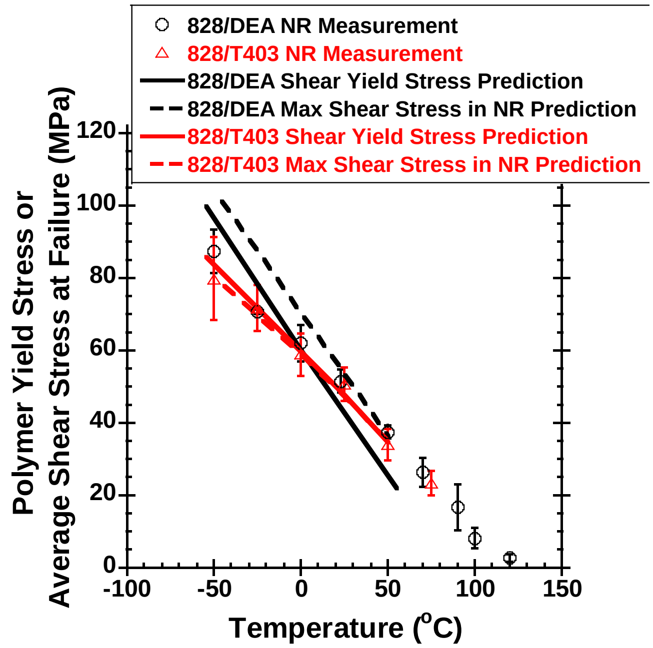

Figure 2. Average shear stress at failure versus temperature for napkin-ring joints bonded with 828/DEA and 828/T403, plotted along with predictions for (1) the adhesive shear yield stress and (2) the maximum stress sustained in a NR joint.

Complementary experiments and computational analyses examined multiple methods to alter the residual stress in the joint and identify any effects on the joint strength that is depicted in Figure 2. Applying a combined axial and torsion load to the joint, as depicted in Figure 3, was identified as the most probable way to resolve the effect of residual stress.

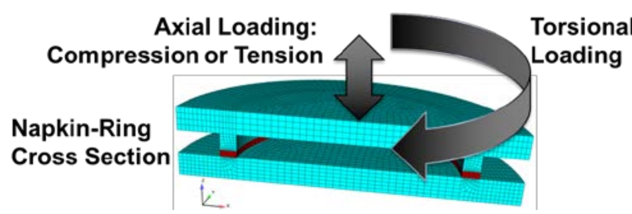

Figure 3. Schematic of NR joint cross section illustrating the modes of loading applied to the joint.

Applying an axial load to the NR joint before applying the torsional load produces a residual stress effect similar to that of a constrained adhesive in the joint that expands/contracts relative to the adherend. The advantage of using the mechanical loading to produce the residual stress is more control over the loading state. Computational predictions of the effect of a controlled axial load on the torsional response of the joint is given in Figure 4.

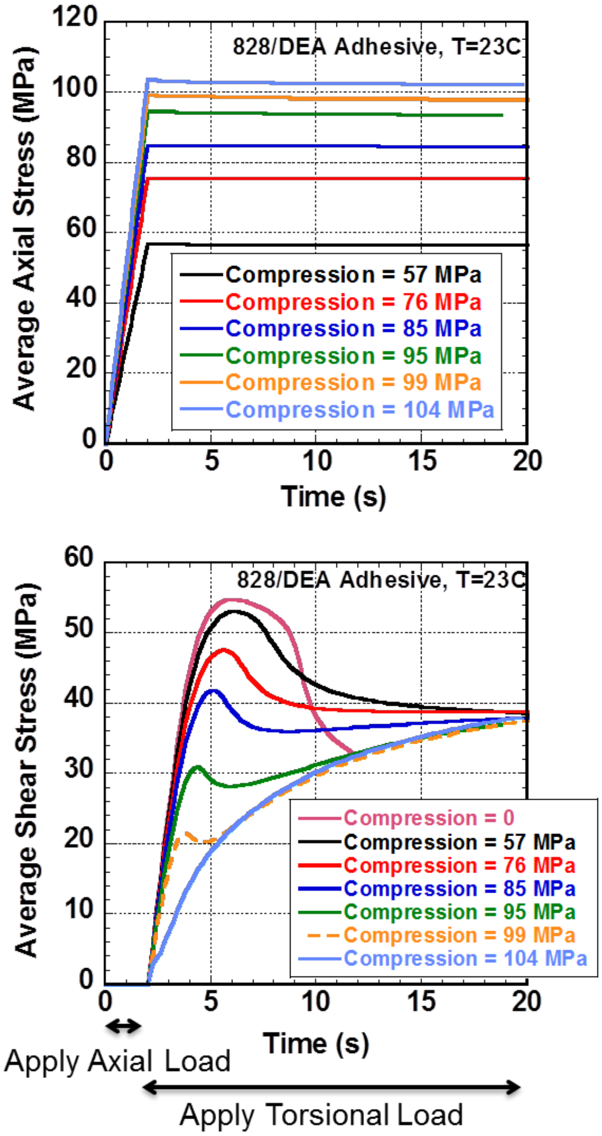

Figure 4. Computational predictions of (a) average axial stress versus time and (b) average shear stress versus time for 828/DEA bonded NR joints. A stress controlled axial load was applied to the joint after cooling from a stress free state at T=75C to T=23C at 0.5C/min under axially free conditions. Immediately after the application of the axial load, a strain controlled torsional load was applied at 0.025 sec^{-1}.

A dependence of the predicted maximum in shear stress during torsional loading is apparent at compressive loads of 57 MPa and above. The implications of this observation and the ability to resolve such an effect experimentally will be discussed in this presentation.

Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

References

1. Bikerman, J. J., *The Science of Adhesive Joints*. 2nd ed.; Academic Press: New York, 1968.
2. http://www.sandia.gov/polymer-properties/828_DEA.html
3. Adolf, D. B.; Chambers, R. S.; Neidigk, M. A. *Polymer* **2009,** 50, (17), 4257-4269.