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Characterization of toughened bonded interface against fracture and impact loads

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Abstract

Joining components of polymer composites through adhesive bonds is becoming increasingly popular. Since the strength of adhesively bonded interface is not high, the interface is designed to be of a large area in most cases. The interface of widely used adhesives like epoxy-based Epibond 1590 A/B is inherently brittle and therefore it is susceptible to fail through fracture. In this study, adhesive Epibond 1590 A/B is modified to make the interface tough by adding a small percentage of high molecular weight carboxylated acrylonitrite butadiene (XNBR). The interface is studied for four candidate proportions 0%, 5%, 7.5% and 10% of XNBR for determining toughness under static and dynamic loading conditions. Modes I and II fracture toughnesses are determined under static conditions and impact-induced damage area of the interface under impact conditions. The Epibond 1590 A/B adhesive modified with 7.5% XNBR by weight gives the best performance for the three properties studied.

Keywords: Epoxy/epoxides; Composites; Fracture mechanics; Impact

1. Introduction

In comparison to welded or brazed joints of metals, adhesives bonds between two components of polymer composites are inferior. Adhesives bonds are therefore designed to have an interface which is large in area. Also, a joint between two polymeric composites are usually designed to subject the bonded interface mostly to shear stress. Since the area of a bonded interface is large, the interface is similar to interlaminar interfaces of a composite laminate and therefore it is likely to fail under impact loads.

The toughness of adhesive interfaces should be characterized for failure against fracture under static and dynamic loading conditions. If two laminates are joined with an adhesive bond the ideal requirement on the bonded interface is that it is at least as tough as that of interlaminar interfaces of the adherends. If this requirement is not met, the adhesive may be further improved to enhance the toughness of the adhesively bonded interfaces.

Epoxy resins are a class of versatile thermosetting polymers and are extensively used in structural adhesives for polymer composites. This is because of their high strength, low creep, very low cure shrinkage, excellent resistance to corrosion, good adhesion to many substrates and appropriate electrical properties. Most adhesives employ polyfunctional epoxy systems with a suitable curing agent. For example, Epibond 1590 A/B is a widely used adhesive. It is a trifunctional novolac epoxy system (Triglycidyl-*p*-aminophenol) with polyamine (Tetraethylenepentamine) curing agent. The epoxy resin cures to form highly cross-linked structure with high strength but it is inherently brittle. This has limited its further proliferation in applications for joining components of polymer composite laminates,

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as there is no fiber reinforcement across the interfaces. Consequently, a resin-rich interface is susceptible to fracture failure and extensive damage under impact loads by foreign objects. This drawback prompted many studies to increase the fracture resistance of the bonded interface.

With the increasing proliferation of the adhesives in structural applications and the hindrance posed due to their brittleness, many researchers were prompted to work towards toughening of the adhesive. Gouri et al. [1] studied the adhesive properties like lap shear strength and T-peel strength of novolac epoxy resin modified with carboxyl-terminated butadiene acrylonitrile (CTBN) solid resin and cured with two different curing agents namely, dicyandiamide (DICY) and 3,3′-diaminodiphenyl sulphone (DDS) using aluminium adherends. Substantial improvements in adhesive properties were obtained by the inclusion of moderate concentrations (15–20% by wt.) of CTBN in the formulations.

He et al. [2] studied the influence of tougher concentration on the behavior of two phase, rubber toughened epoxy. They showed that the toughness increased to a maximum and then decreased as the concentration is increased. Kumar and Singh [3] studied the impact damage area and interlaminar toughness of FRP laminate by modifying the epoxy resin with the addition of CTBN 1300X8 and triphethylphosphine under a controlled atmosphere of inert nitrogen gas. When impacted by a steel projectile they found a significant reduction in damage area. Zhang et al. [4] synthesized a series of novel toughening agents defined as LCEU containing both flexible chain and rigid rod like moiety and used to modify the epoxy resin (E-51)/DICY curing system. They showed that the modification yielded good results and the impact strength was increased considerably. Imanaka et al. [5] investigated the crack propagation in epoxy adhesives filled with spherical silica using double cantilever beam (DCB) specimens. As compared to unmodified epoxy-bonded specimen the fracture toughness was found to be higher. Also, the fracture toughness was found to increase with particle size in the range of 6–30 μm. Imanaka et al. [6] also investigated the fracture toughness of rubber-modified epoxy-bonded joints. Adhesively bonded CT and SENB specimen were tested. The crack extension was found to be very small and the J-integral value was found to increase with enhanced plastic deformation.

Varley et al. [7] examined the effect of addition of a thermoplastic rubber [Polysulphone (PSF)] to the epoxy resin and compared the differences in the network structure and properties of the system. Ochi et al. [8] modified a bisphenol-type epoxy resin which had a mesogenic group in backbone moiety with reactive elastomer (CTBN). They found that toughness of epoxy resin was significantly increased with the addition of CTBN elastomer compared with that of bisphenol-A type epoxy resin. Chikhi et al. [9] modified diglycidyl ether of bisphenol-A epoxy resin with liquid amine-terminated butadiene acrylonitrile (ATBN) copolymer containing 16% acrylonitrile at different contents. They observed improvement in the izod impact strength, critical SIF and tensile properties of the modified epoxy with a decrease in glass transition temperature.

Marieta et al. [10] used atomic force microscopy to determine the microstructure of thermosetting matrices toughened by incorporation of core shell particles and high-performance thermoplastics. They used AFM to analyze the influence of modifiers and the curing conditions on the generated morphologies. Duncan and Dean [11] proposed that the cavitation model accurately predicts the behavior of rubber toughened adhesives. Varley [12] evaluated three low viscosity polymers namely CTBN, epoxy-terminated hyper-branched polyester and an aminopropyl-terminated siloxane. He showed that the epoxy-terminated hyper-branched polyesters can be used effectively to toughen the lower cross linked epoxy resin systems.

Polymer composites have poor translaminar properties which make them particularly susceptible to impact loads. Such damages are not detectable to the normal eye (the damage being in the substrate region or being too small to be visible to the naked eye), which adds to the critical nature of the low velocity impact damage. Therefore, it has been a subject of particular attention of researchers worldwide. The available literature has concentrated mostly on two aspects. The first one deals with experimental and theoretical investigation of the effect of impact-induced damage on the post-impact compressive strength. The second aspect concerns the relationship between the impact energy and the size of damage area.

Choi and Chang [13] predicted the shape and size of impact-induced delaminations in cross ply and quasi-isotropic graphite/epoxy laminates using three-dimensional solid brick elements. Siow [14] found that the predominant damage mechanisms for woven laminates were delamination and fiber breakage with the area of impact-induced delamination increasing linearly with impact energy. Sankar [15] carried out numerical simulation to predict the effects of stitching on the low-velocity impact response of delaminated composite beams by modeling the effect of stitches as constant shear traction in the stitch bridging zone to account for the shear resistance offered by unbroken stitches. Similarly, Hosur et al. [16] investigated the damage resistance of stitched/unstitched S2-glass/epoxy composites.

In this study, the widely used epoxy-based adhesive Epibond 1590 A/B is modified with carboxylated acrylonitrile butadiene (XNBR) to enhance the toughness of adhesively bonded interface. Other modifiers (CTBN, ATBN) also enhance the toughness but the