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The mixed-mode fracture behavior of epoxy by the compact tension shear test

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ABSTRACT

In this study, pure mode I, pure mode II and mixed mode fracture behavior of an epoxy were investigated. Specifically, the mixed mode values of fracture toughness and critical strain energy release rate (CSERR) were measured. Specimens were subjected to mixed mode loading using compact tension shear (CTS) test. Some experimental modifications were found to be necessary to eliminate rotation and ensure crack propagation at the notch when testing epoxy specimens at high mode II loading. A failure criterion for the mixed mode loading of polymer is developed and its predictions are compared with the experimental results. The crack propagation direction in epoxy was investigated in this research as well. A detailed study of failure mechanisms on the fracture surface was performed. The results indicate that the increase in the value of toughness can be directly related to the fracture morphology.

1. Introduction

The prediction of the fracture behavior of polymer composite materials is a complex undertaking that has necessarily involved at least some degree of empiricism [1–4]. With the long-term goal of being able to design composite systems for optimized energy absorption, it would be highly beneficial to develop a predictive fracture model that is based solely on the properties of the constituent phases, the interface between them and the geometric details of the microstructure. Owing to the high degree of constraint resulting from closely packed fiber reinforcement, the matrix of a polymer composite shares similarities with adhesive joints, in this paper, we begin with the characterization of a common epoxy system subjected to mode I, mode II and mixed mode I/II loading as a first step on the path to a predictive model for the mixed mode fracture polymer composite systems. To obtain such a model it is required to study the fracture behavior of bulk polymer and to relate the amount of energy released in the fracture of the polymer to the energy released in the fracture of a confined polymer in a polymer composite or a bonded joint. The full investigation of polymer fracture is carried out in this research.

2. Background

The study of mode I toughness in polymers and polymer joints has been performed by several researchers using bend test or compact tension specimen [5–8]. However, the mixed mode fracture toughness of neat polymer has been studied by few researchers. Maccagno and Knott [9] studied the mixed mode behavior of PMMA using four-point bending test of a beam and they compared their results with three fracture criteria. They concluded that a maximum tensile stress criterion well-described the material behavior. Chen et al. [10] used J-integral contour to compute mixed mode strain energy release rate in polymer bonds. Araki et al. [11] investigated the mixed mode crack angle of an epoxy and compared it with the existing criteria. They also studied the effect of the glass transition temperature on the toughness. The measurement of mixed mode fracture response of epoxy was carried out using beam specimens subjected to three-point or four-point bending tests. Apart from reporting the values of toughness and comparing them with empirical failure criteria, the contribution of the fracture mechanisms to the value of toughness was not studied by these researchers. Bruce [12] compared the fracture surface of polymer specimens subjected to pure mode I and pure mode II loading and found the mode II CSERR to be 2.4 times greater than the mode I value. Observations of the respective fracture surfaces revealed that the mode II surface consisted of 45° hackles compared to the flat surface of the mode I specimens and led to the conclusion that in increased mode II CSERR is due to solely the increased crack path length, $L = L_0(1 + \sqrt{2})$, resulting from hackle formation.

To study mixed mode loading, the beam methods require different types of specimens or testing for different modes of loading. However, the CTS test described by Richard [13] requires only one specimen geometry for the whole range of mixed mode loading.

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3. Experimental method

3.1. Materials and manufacturing

The neat epoxy specimen in this study was made using CLR1180/CLH6560 epoxy material from Crosslink Tech. Inc. The epoxy was made by mixing hardener and resin in a ratio recommended by the manufacturer (100 units of resin to 30 units of the hardener). In mixing the resin and the hardener, particular care was taken to avoid introducing air bubbles into the mixture. After mixing, the resin was poured into trays or molds that were lined with Teflon vacuum bags to avoid resin adhering to the trays. The

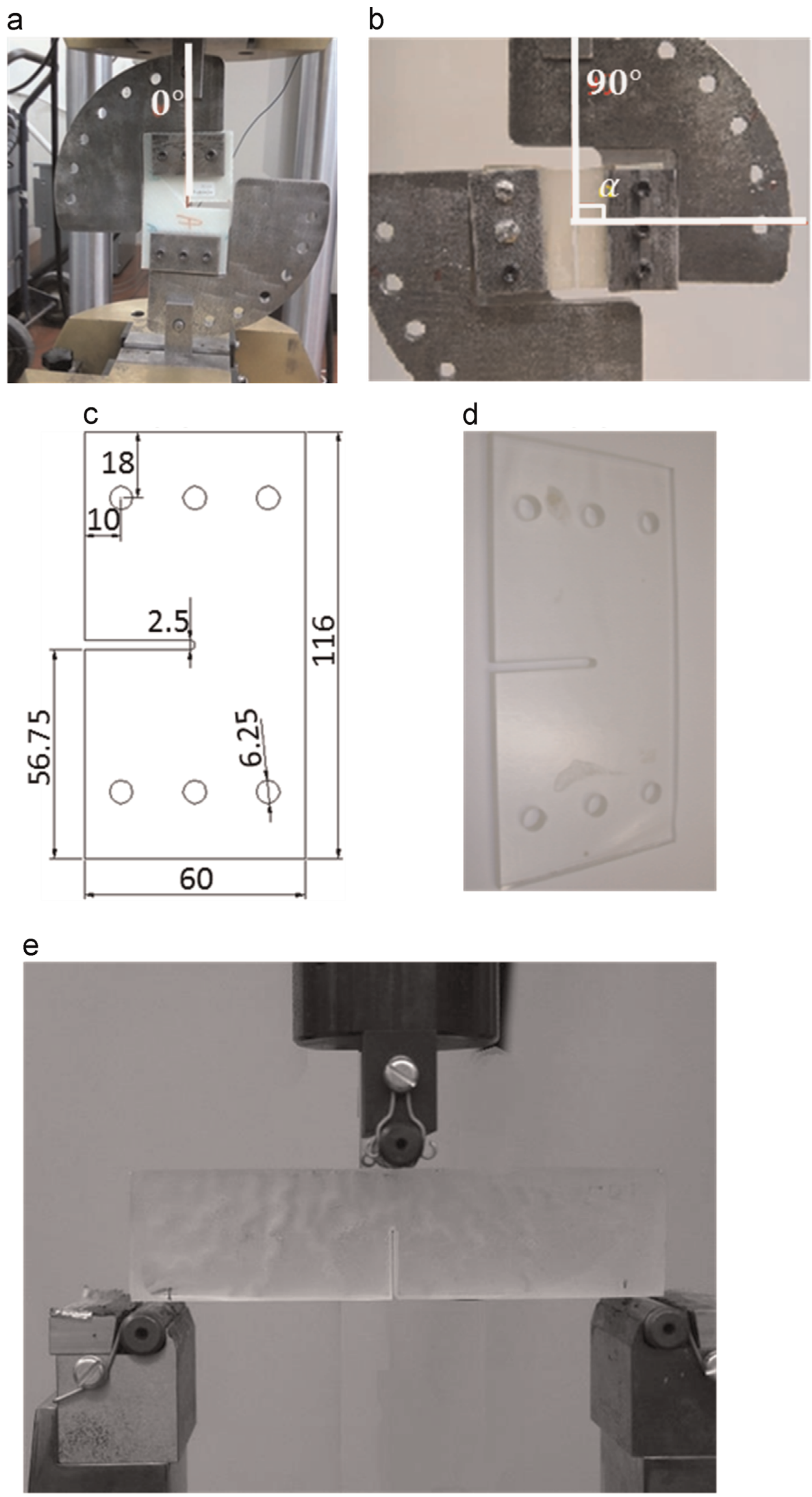

Fig. 1. CTS fixture. (a) pure mode I. (b) pure mode II loading. CTS specimen (c) 2D drawing (d) neat epoxy specimen after machining. (e) Single edge notch beam lab setting.