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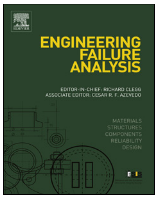

Fractographic study of damage mechanisms in fiber reinforced polymer composites submitted to uniaxial compression

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ABSTRACT

After the advances of microscopic techniques, the literature shows an increasing number of fractographic studies of fiber reinforced polymer composites. However, the fractographic aspects of compressive failures remain slightly explored and poorly enlightened. In this context, the purpose of this work is to present some of the main mechanisms responsible for the fracture energy absorption in the case of fiber reinforced polymer composites submitted to compressive loads. To do so, this study used an extensive literature review in addition to fractographic studies of textile carbon fiber/epoxy composite laminates, which were manufactured using prepreg scraps from the manufacturing waste of aeronautical industry. It was possible to identify the main damage mechanisms which occur in compressive failures of fiber reinforced polymer composites, namely microcracking, crack bridging, protrusions (not commonly reported in the literature) and fiber microbuckling leading to kink-band formation. Thus, we intend to contribute to a better understanding of the compressive behavior of polymer composites as well as of the resulting fractographic aspects.

1. Introduction

The use of fiber reinforced polymer composites in replacement of conventional materials (e.g., aluminum alloys) grows with advances in manufacturing technologies [1]. Albeit, this class of materials exhibits an intricate damage process, which hinders the comprehension of their response to complex loading conditions [2]. Furthermore, depending on the microstructure of the composite and on the loading condition, damage mechanisms can interact enhancing the complexity of the fracture process [3].

In fact, a number of damage mechanisms may act absorbing energy during the fracture propagation [4], among which can be cited interfacial debonding, interfacial sliding (resulting in fiber pull-out), matrix microcracking (intralaminar or translaminar), interlaminar cracking (delamination), fiber breakage, fiber microbuckling, particle cleavage and void growth [5]. The proper understanding of these damage mechanisms is essential to tailor the behavior of fiber composites to the design requirements. One example is the multiple cracking that induce pseudo strain-hardening in brittle matrix composites, as reported by Li and Leung [6]. More recently, the interaction between delamination, fiber breakage and matrix microcracking has been used to promote a pseudo-ductile behavior in fiber reinforced polymer composites submitted to tensile loads [7, 8].

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Concerning the compressive failure, the analysis of the fracture surface is troublesome, since the mating fracture surfaces are pressed against each other, which difficult the identification of the morphological aspects [9, 10]. This is reflected in the lack of knowledge of the mechanisms that lead to compression failure [11]. According to Greenhalgh and Hiley [12], the fractography is the key to better understand the physical mechanisms of composite fracture.

In this context, our research group have been studying the fractographic aspects of fiber reinforced polymer composites submitted to axial compression [13–15]. Particularly in this work, the damage mechanisms typical of failures in compression are studied from a fractographic perspective. The main goal is to exemplify the fractographic aspects of such mechanisms in the case of compressive loadings, which are done based on observations of different groups of fiber reinforced polymer composites as well as a literature review.

2. Materials and methods

As aforementioned, the study here presented was carried out based on an extensive literature review in addition to experimental observations, which were performed on polymer composite specimens submitted to axial compression. The specimens studied were manufactured using prepreg scraps from the aeronautical industry waste. The used prepregs consisted of carbon fibers in plain weave textile architecture, impregnated by a toughened epoxy matrix (HexPly F155, Hexcel Composites). The scraps were randomly positioned over a flat jig, without a preferential fiber orientation. The manufactured composite laminates were cured in autoclave, at 180 °C and 0.7 MPa. More details about the manufacturing and morphological aspects of the composite laminates produced can be found in previous works of our research group [14, 16].

The compression tests were performed following the recommendations of the SACMA SRM 1R-94 [17] standard (derived from the ASTM D695 standard), in which the compressive loading is applied at the end of the specimens. A total of 60 specimens were tested in an universal testing equipment (MTS Criterion™), with 1.0 mm/min displacement speed. As these tests were performed to assess the compressive strength, the specimens were tabbed, leaving a gage length (untabbed region) of approximately 3.0 mm. The other dimensions of the specimens were 80.0 mm, 15.0 mm and 3.0 mm, respectively for the length, width and thickness. Finally, the test fixture used is comprised of two parallel “V” grooved plates, to provide lateral support inhibiting buckling.

Hygrothermal conditioning preceded the tests of 30 specimens, in accordance to ASTM D5229 standard [18]. The conditioning was carried out in a hygrothermal chamber (Marconi MA 835/UR), with a temperature of 82 ± 3 °C and 95 ± 5% moisture. Four traveler specimens were used to evaluate the mass gain, by which it was determined that the moisture equilibrium condition was achieved after 8 weeks with a total mass gain of 0.37%. The fractographic observations here presented were performed using a scanning electron microscope (TESCAN - Vega 3 XMU).

3. Results and discussion

According to Talreja and Singh [5], the heterogeneous microstructure of composites, the presence of interfaces as well as the inherent anisotropy of this material class are the main reasons for the complex failure process of composite materials. This is particularly true in the case of compressive loads, in which the relative movements of the fracture surfaces promote post-failure damages.

Regarding the failure analysis, besides the characteristic aspects of the compression failure modes reported in the literature [2, 14, 15, 19–21], it is possible to identify aspects related to damage mechanisms. The occurrence of these mechanisms implies on a greater absorption of the fracture energy and usually results in a higher strength. As will be seen, some damage mechanisms are typically associated with compressive damages, and some of them are common to other loading conditions, but assume a particular configuration in the case of compressive loads.

3.1. Microcracking

Microcracks are likely the most common among the possible damages mechanisms in compressive failure. The formation of microcracks is common to all compression failure modes, as a way of stabilizing the crack propagation by creating new fracture surfaces, which leads to higher energy absorption [22, 23]. Fig. 1 show examples of the occurrence of microcracks (pointed by white arrows) in different types of failures modes, namely, longitudinal cracking failure (Fig. 1a), wedge splitting failure (Fig. 1b) and through-the-thickness shear failure (Fig. 1c).

According to Chakachery and Bradley [24], microcracking precedes the propagation of interlaminar cracks, being the coalescence of these microcracks that promotes the delamination growth. In this way, microcracking can be seen as an intrinsic characteristic of interlaminar failures, even though been common to all failure modes. According to the classification developed by our research group [13], the interlaminar failures are the ones where the fracture process is dictated by the interlaminar shear strength, i.e. by the resistance to delamination growth. However, aside from the microcracks that induce delamination growth, the interlaminar failures exhibit other kinds of microcracks typically seen in these failures. For example, in the case of longitudinal cracking failures the crushing of the layers promotes the formation of translaminar microcracks, as seen in Fig. 1a.

While in case of delamination buckling failures, mainly for bidirectional reinforcements (e.g., textile composites, cross-ply laminates), there is a tendency of translaminar microcracks and transverse intralaminar microcracks to occur due to the bending of the layers. These microcracks are formed in layers (in case of cross-ply laminates) or in fiber tows (in case of textile composites) that suffered buckling, as shown in Fig. 2. The translaminar microcracks occur due to the flexural failure of the fiber aligned with the