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Composites Science and Technology 65 (2005) 2550–2562
COMPOSITES SCIENCE AND TECHNOLOGY
www.elsevier.com/locate/compscitech

Strengths of C/C composites under tensile, shear, and compressive loading: Role of interfacial shear strength

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Received 1 April 2005; received in revised form 8 July 2005; accepted 12 July 2005
Available online 24 August 2005

Abstract

Various strengths of carbon–carbon composites (C/Cs) are comprehensively reviewed. The topics reviewed include tensile, shear, compressive, and fatigue strength as well as fiber/matrix interfacial strength of C/Cs. When data are available, high temperature properties, including creep behavior, are presented. Since C/Cs have extremely low fiber/matrix interfacial strength τ_d, the interfacial fracture plays important roles in all of the fracture processes dealt in this review. The low τ_d was found to divide tensile fracture units into small bundles, to seriously degrade both shear and compressive strength, and to improve fatigue performance. In spite of the importance of the interfacial strength of C/Cs, techniques for its evaluation and analysis are still in a primitive stage.

Keywords: A. Carbon fibers; B. Interfacial strength; Strength; Stress/strain curves

1. Introduction

Carbon fiber-reinforced carbon matrix composites (C/Cs) exhibit superior thermo-mechanical properties even at elevated temperatures above 2000 K. In light of this advantage, C/Cs are expected to be applicable for use in high-temperature structures [1–4]. However, the mechanical behavior of C/Cs has not been fully elucidated to the extent that their mechanical properties can be tailored to certain purposes as in the cases with fiber-reinforced plastics and ceramics. Thus, C/C structures have been designed on a trial-and-error basis, and therefore lack sufficient reliability for use in primary load-bearing structures. As a result, the applications of C/Cs have been restricted to structures in which high strength is not required, but rather in which only high-temperature capabilities are necessary. Recently, the present authors and their colleagues have expended a significant amount of effort toward the clarification of the mechanical behavior of C/Cs especially from the viewpoint of fracture mechanisms [5–10]; thus far, most of fracture processes of C/Cs have been found to profoundly affected by their fiber/matrix interfacial properties. The present review deals with such recent progress regarding the strengths of C/Cs, including studies of their tensile, shear, compressive, and fatigue strength as well as fiber/matrix interfacial strength. Based on recent findings, special attention is paid to the relationship between these fracture mechanisms and the roles played by fiber/matrix interfacial strength.

2. Fiber/matrix interface of C/Cs

2.1. Interfacial shear strength at room temperature

Several attempts have been made to measure the fiber/matrix interfacial shear strength of C/Cs using

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doi:10.1016/j.compscitech.2005.07.012

methods often adopted for other composites, i.e., polymer matrix and ceramic matrix composites [11–17], including fiber push-in, push-out, and pull-out tests [18–22]. However, to date, the interfacial shear strength of C/Cs has been successfully determined only by fiber push-out tests [9,21,22]. The difficulties associated with the determination of the interfacial strength of C/Cs are twofold. First, the carbon fiber is prone to compressive failure upon compressive axial loading. This tendency is especially noticeable in the case of pitch-derived fibers. Accordingly, a specimen must be prepared such that interfacial debonding readily occurs at a sufficiently low load. This means that the specimen should be extremely thin and less than approximately 100 μm. However, in such a case, the fiber/matrix interface is often damaged during specimen preparation. The second difficulty in this context is the thickness of the carbon fibers, which are around 5–10 μm in diameter. Hence, the application of load precisely at the center of fiber cross-sections and confirmation of damage at such an interface remain rather difficult [21]. Thus, the utilization of the single fiber push-out test was limited to polyacrylonitrile (PAN)-based carbon fibers, and to specimens with weak interfaces.

In order to avoid such difficulties, we attempted a fiber bundle push-out test. The procedure of this test is illustrated in Fig. 1. In this test, an indenter with 50 μm in diameter was successfully employed [9,23]. Thus, the diameter of pushed-out bundle is large and the thickness of specimen can be set about 100–300 μm. Observation of pushed-out bundles ensured that fiber/matrix interfacial fracture dominated fracture surface. This result guaranteed reliability of this test method. However, the single and bundle push-out tests resulted in different interfacial strengths [21]. Accordingly, the present methods are useful in comparative purpose, but insufficient for measurements of quantitative physical values.

Typical results obtained by the fiber bundle push-out tests are shown in Figs. 2 [9] and 3 [24,25] for C/Cs reinforced with PAN-based fiber IM-600 and pitch-based fibers K321 and K633, respectively. In Fig. 2, 2D-RC-2573K and 2D-HIP-2573K represent IM-600-C/Cs with cross-ply lamination (2D) densified by the resin char method (RC) or the hot isostatic pressing method (HIP) and heat-treated at 2573 K. The fiber volume fraction (V_f) in the precursor (carbon fiber-reinforced phenolic resin) of these C/Cs was 60%. As this figure shows, the interfacial sliding stress τ_s and the debonding stress τ_d were enhanced with increase in density ρ, and the ultimate tensile fracture strain ε_b was degraded with

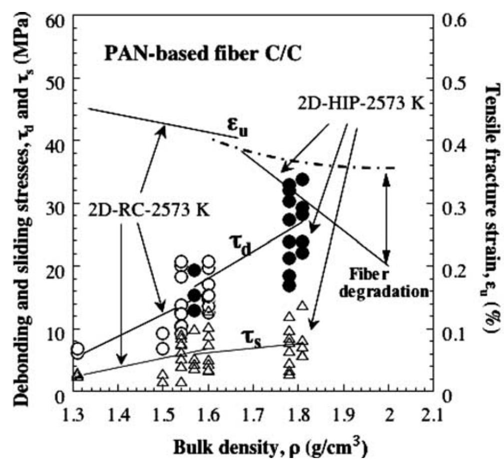

Fig. 2. Tensile fracture strain, ε_u, interfacial debonding stress, τ_d, and interfacial sliding stress, τ_s, of a cross-ply-laminated C/C reinforced with PAN-based fiber IM600 as a function of bulk density, ρs densified by the repeating resin char method (RC) and the hot isostatic pressuring method (HIP) [9].

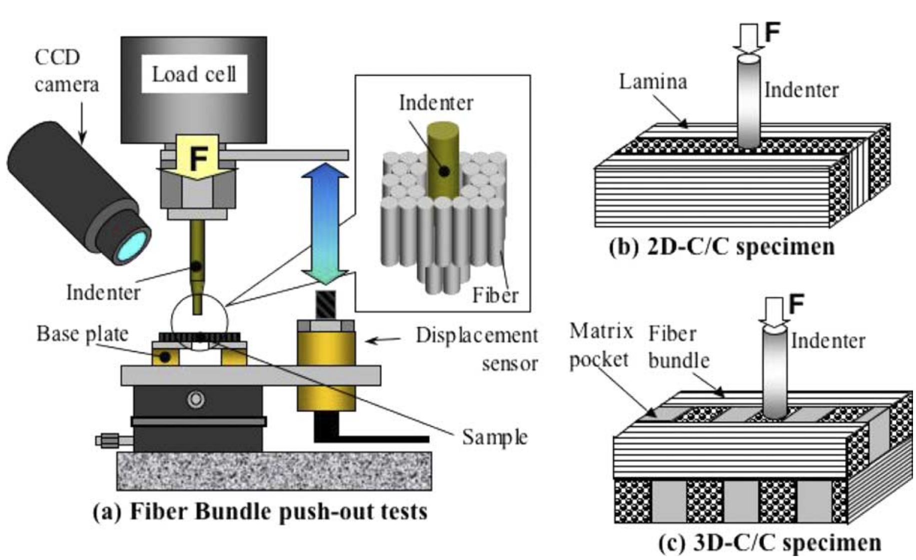

Fig. 1. Schematic drawings of the fiber bundle push-out test. Test fixture (a), specimen arrangement for 2D-C/C (b) and 3D-C/C (c).