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Longitudinal direct compression test of a single carbon fiber in a scanning electron microscope

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ABSTRACT

Longitudinal direct compression testing of a single polyacrylonitrile-based carbon fiber (T800S) is performed with a piezo-actuated testing machine installed in a scanning electron microscope, and the longitudinal compressive behavior of a carbon fiber is observed during loading. The compressive stress–compressive strain relation is linear in the early phase, and then becomes non-linear. The longitudinal tangent modulus in the compression decreases with increasing compressive strain. The failure strain seen in compression is much higher than that in tension. The variability of the compressive strength is evaluated via Weibull analysis, and is found to be smaller than the tensile strength variability. The compressive fracture surface is irregular and possesses a serrated morphology that is different from the tensile fracture surface. The representative strength ratio of the compressive to tensile strengths of the carbon fiber is ≈0.5, which almost matches the compressive to tensile strengths ratio of the unidirectional carbon fiber reinforced plastic.

1. Introduction

The longitudinal tensile strength of unidirectional carbon fiber reinforced plastic (UD CFRP) has been increased by increasing the tensile strength of the reinforcing carbon fibers, but the longitudinal compressive strength has not been increased. The relation between the longitudinal compressive versus tensile strengths of various UD CFRPs clearly indicates an unbalanced mechanical property, and especially for UD CFRP made of a high tensile strength carbon fiber, as shown in Fig. 1 [1–4], where the compressive to tensile strength ratio is ≈0.5.

Kink-band failure, wherein in-phase micro-buckling of fibers occur within the polymer matrix, is a typical mode of longitudinal compressive failure in UD CFRP [5] and is known as the primary cause of its low compressive strength. Analytical and numerical models have been proposed to predict this kind of failure [6–9]. The models require knowledge of the compressive property of the carbon fiber to predict kink-band failure. A direct compression test of a single carbon fiber is a sound method to measure the compressive property because of its simplicity, but the test is not easy because a carbon fiber is a fine thread with a nominal diameter of 5–10 μm. The loop and recoil tests have been proposed to indirectly measure the compressive strength [10], but these testing methods include some assumptions to obtain the compressive strength, so a direct compression test is still needed.

Some pioneering reports of a direct compression test on a single carbon fiber are available [11–13], but the direct compression test does not meet widespread acceptance because of the difficulty of executing the test and the uncertainty that accompanies a blind test owing to its microscopic scale. In-situ observation of a carbon fiber undergoing a direct compression test is needed to create confidence in the test, and the improved test apparatus that now exists needs to exhibit a more reliable direct compression test.

In this study, the basic approach to perform a longitudinal direct compression test of a single carbon fiber is proposed. A direct compression test is performed using a piezo-actuated testing machine, which is installed in a scanning electron microscope (SEM), and the compressive behavior of the carbon fiber is observed during the loading. The applied compressive load is measured by a load cell, and the contraction of the carbon fiber during the loading is measured by the SEM. The compressive stress–compressive strain relation of a single carbon fiber is obtained, and the variability of the compressive strength is discussed by means of Weibull analysis and compared with the tensile strength variability. In this way, the compression property of a single carbon fiber is compared with its tensile property.

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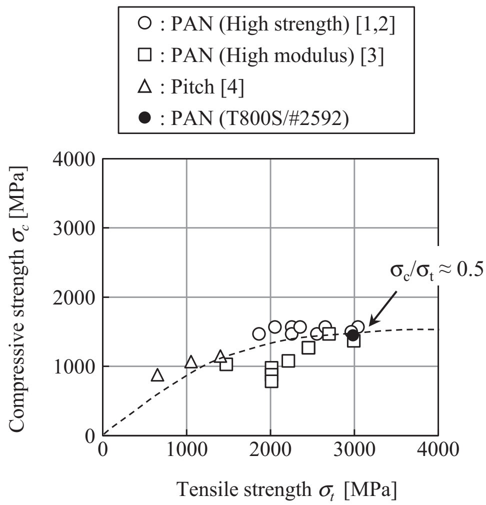

Fig. 1. Longitudinal compressive strength verses longitudinal tensile strength of various UD CFRP samples [1–4]. The measurements for T800S/#2592 are obtained by the author (tensile strength: 2980 MPa; compressive strength: 1450 MPa; fiber volume fraction: ≈65%).

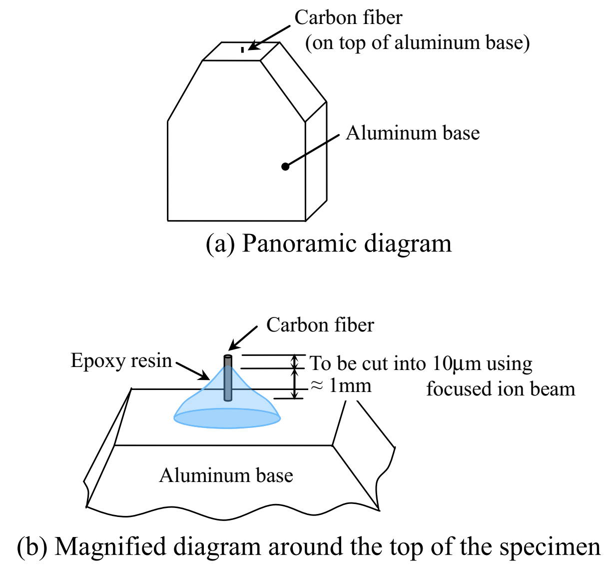

Fig. 2. Schematic of a carbon fiber specimen. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Experimental

2.1. Carbon fiber specimen

2.1.1. Gage length of a single carbon fiber

To measure the longitudinal compressive property of a single carbon fiber, fiber buckling needs to be prevented in the longitudinal compression test by determining the appropriate fiber length. Assuming the end conditions of the fiber as one end fixed and the other free (described in more detail in Section 2.1.2), the critical buckling load (P_{cr}) of an Euler column is given as:

$$P_{cr} = \frac{\pi^2 EI}{4L^2}, \quad (1)$$

where E is Young's modulus, I is the moment of inertia and L is the length of the fiber. Taking the compressive property of the fiber to be equal to the tensile property, the length of a carbon fiber required to prevent buckling during the longitudinal compression test is given as:

$$L \leq \frac{\pi d}{8}\sqrt{\frac{E}{\sigma_f}}, \quad (2)$$

where d is the fiber diameter and σ_f is its tensile strength.

A polyacrylonitrile (PAN)-based carbon fiber (T800S, Toray) was used in this study because of its circular and uniform axial cross-section along the fiber direction and its low surface roughness, which enabled easy assessment. The carbon fiber was supplied as sized (10E) for epoxy resin, and the mechanical property of the carbon fiber is given in Table 1 [14]. The carbon fiber length required to prevent buckling was calculated using Eq. (2) to be less than 14 μm when the mechanical property of the fiber in compression was taken to be the same as that in tension. In this study, a length of 10 μm was adopted.

Table 1
Mechanical properties of the T800S carbon fiber [14].

Tensile Young's modulus	294 GPa
Tensile strength	5880 MPa
Tensile failure strain	2.0%
Fiber diameter	5 μm

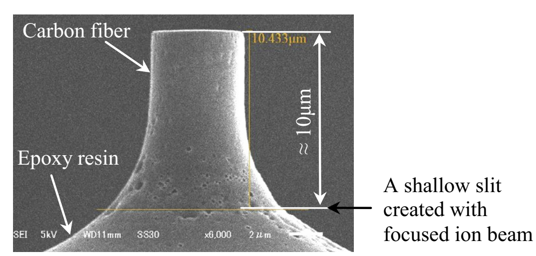

Fig. 3. The tip of the specimen. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.1.2. Configuration of specimen

The specimen configuration is shown in Fig. 2. In this setup, the side of an aluminum base was machined into a trapezoidal shape, and epoxy resin (105/206, West system) was affixed to the top surface of the trapezoidal section, into which a carbon fiber was vertically inserted using an *XYZ* stage. The length of the carbon fiber which was inserted into the epoxy resin was about 1 mm. The epoxy resin was cured for more than 24 h at room temperature, holding the carbon fiber in place using the *XYZ* stage, after

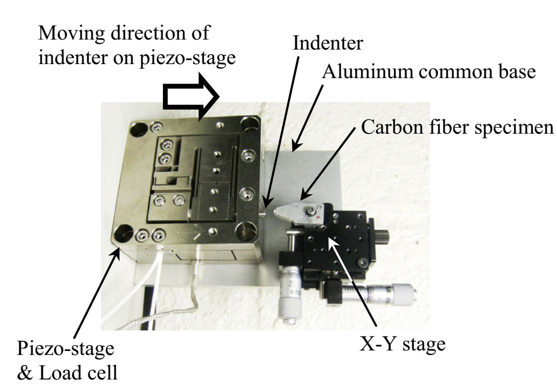

Fig. 4. Miniature testing machine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)