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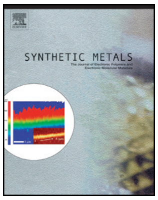

Monitoring self-sensing damage of multiple carbon fiber composites using piezoresistivity

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ABSTRACT

The change of electrical resistance in small bundles of multiple carbon fibers and multiple unidirectional carbon fiber/epoxy composites with applied tensile strain has been investigated. The electrical resistance of bundles initially increases relatively slowly in a stepwise manner with increasing strain due to fracture of peripheral fibers. This regime corresponds to the linearly increasing part of the load-strain curve. At higher strain, a progressive fracture of inner fibers in the bundle associated with flat region of load-strain curve leads to concomitant sudden rise of resistance. When the whole sample undergoes major failure, the slope of the load-strain curve becomes negative while the relative resistance increases abruptly to infinity. In strands of carbon fibers slightly impregnated with epoxy the change of resistance is affected by the thickness of epoxy layer surrounding the fibers. We demonstrate that volume fraction of fibers as well as initial number of fibers in the epoxy determines the piezoresistance properties of the specimen. Broken fibers can come into electrical contact with unbroken fibers and thus participate to the overall resistance of the specimen. As a result the dependency of relative resistance versus increasing applied strain presents stepwise behaviour also in the high strain region that is attributed to fiber fracture. In contrast to the bundles of bare carbon fibers, the stress-strain curves of the composites demonstrate monotonous linear increase in both low and high strain regions. The relative resistance goes to infinity when all remaining unbroken fibers undergo fracture.

1. Introduction

Composite materials play a major role in modern life and technology due to their stiffness, strength, shaping, and lightweight [1]. Applications are multiple and cover many areas of industry such as buildings, wind turbine blades, aircrafts, spacecrafts, cars, boats, etc. The most worldwide spread composites are made from an epoxy matrix reinforced by glass or carbon fibers. Such composites are durable and resistant to fatigue, shocks, fire, weathering [2]. However, composite materials loaded beyond their critical value can fracture abruptly necessitating simple and robust real time methods for detecting *in-situ* fiber damage under loading. An accurate technique consisting in embedding small optical strain sensors in an epoxy composite has recently been developed that is able to record in real time the thermal and mechanical strain during composite fabrication [3]. Another approach is to use self-sensing techniques in laboratory-scale experiments. Indeed, an interesting multifunctional property of carbon fibers (CF) used as reinforcement in epoxy matrix is their piezoelectrical behaviour manifested as a change of CFs electrical resistance with applied strain [4,5]. The strain sensitivity properties of carbon fibers have been explored by several groups that demonstrated the possibility to detect strain-induced damage in bare single carbon fiber using piezoresistance measurements [6,7]. Thus, piezoresistive characteristics measured *in-situ* can be used to monitor mechanical properties of individual fibers, bundles of multiple fibers and their polymer matrix composites [8]. Therefore, in-situ strain self-sensing of carbon fibers embedded in polymeric matrix would make it possible to avoid implementation of external or internal strain sensors which might be detrimental to the composite properties [9]. Moreover, this non-destructive, sensitive and precise monitoring technique does rely only on one key

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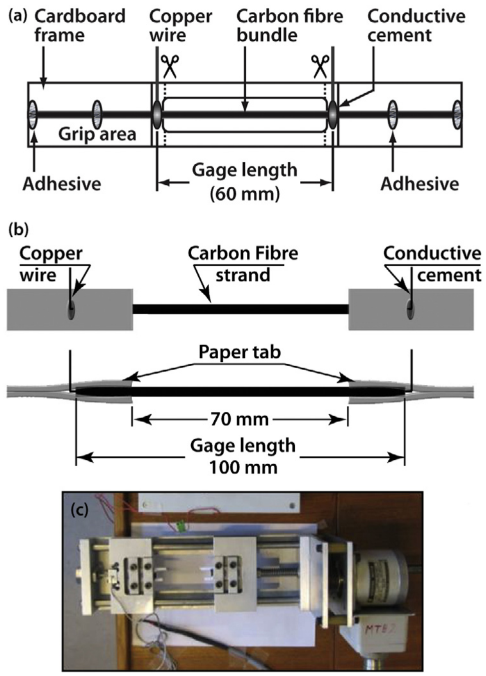

Fig. 1. Schematic illustration of (a) carbon fiber bundle and (b) multiple CFRP strand specimens for the electromechanical test; (c) a home-made straining rig for piezoresistivity measurement.

component of the composite that is the carbon fibers. In a recent work, we have improved this self-sensing technique by combining piezoresistivity and in-situ micro-Raman measurements in order to determine the relationship between the straining of a single carbon fiber embedded in an epoxy matrix and its relative electrical resistance [10].

In the current work we report on the electromechanical properties of carbon fiber bundles and strands. The latter consists of small CF bundles impregnated with epoxy resin. Two fiber grades are used with different surface treatments to show that fiber damage and interfacial properties in multiple unidirectional CF/epoxy composite systems can be efficiently probed by this method. The electromechanical technique applied to the carbon fiber bundles and the composite strands provides highly suitable and precise tests for estimating in-situ fiber and composite damage in the systems studied here. The present investigation focuses in particular on the piezoresistive effects of two different structural parameters such as the volume fraction and the number of carbon fibers in the studied composite models.

2. Experimental

2.1. Materials and specimen preparation

Multiple carbon fiber specimens, i.e. multi-CF bundles, were prepared following the procedure already described elsewhere for single fiber specimens [10]. In this case a bundle of carbon fibers of the same length (the gage length of 60 mm) and grade (high and low modulus) was very firmly attached with cyanoacrylate adhesive to a specially designed rectangular hollowed out cardboard frame (Fig. 1a). The bundle is running along the long axis of the frame and cannot undergo slippage under subsequent applied strain. An electrical contact between a copper wire and the fiber bundle was established by means of conductive carbon paste cement brushed onto the cardboard frame.

The carbon fibers used in this work were high modulus HM35 of 6.7 μm in diameter (HM, Toho Tenax) and low modulus Pyrofil TR50S of 7 μm in diameter (LM, Grafil Inc) that were supplied as untwisted 12000-filament tows treated with an epoxy-compatible material hereafter referred to as sizing. This thin coating protects the carbon fiber surface and enhances the interfacial properties of composite materials. The unsized (without epoxy-compatible material) configuration of TR50S fibers was also available from the manufacturer while a specific heat-treatment was carried out on the sized HM35 carbon fibers to achieve their coating-free configuration. It has been reported by Feih et al. that complete fiber sizing removal can be difficult [11]. These authors performed a heat-treatment at 500 °C with an isotherm of 2 h, which appeared to be insufficient. Therefore, in the present work the heat-treatment duration of the HM35 fibers with sizing was increased to 4 h at 600 °C in order to avoid such problems. The atmosphere was controlled with a continuous flow of nitrogen.

Carbon fiber epoxy composites, i.e. carbon-fiber reinforced polymeric (CFRP) strands, were manufactured using the same two carbon fiber grades described above. The polymeric system chosen in each case was epoxy LM E20 mixed with a hardener LM H20 that are provided by LM Wind Power. Mechanical and electrical properties of both carbon fiber grades with sizing and epoxy resin are shown in Table 1. Single bundles of sized and unsized fibers were impregnated with a mixture of three-part epoxy resin and one-part hardener. Samples were prepared by pulling the bundles through the resin bath at room temperature. The curing cycle of this specimen was similar to that used for single carbon fiber/epoxy composite fabrication described elsewhere [11]. Curing was achieved at 80 °C for 4 h with subsequent post-curing at 120 °C for 0.5 h. CFRP strands comprising of 11 to 32 fibers were fabricated.

After post-cure, carbon fiber-epoxy strands were sectioned transversely to their long axis, and characterized by scanning electron microscopy (SEM) to determine the volume fraction of fibers. Since the strands had irregular cross-sectional shapes the fiber volume fractions were estimated with the following method. Images of the cross-section were printed on paper. The whole specimen section and the individual carbon fiber section images were cut and weighed with a precision balance. Since the mass of paper measured for these objects should be proportional to the image areas, it was assumed that their mass ratio can give an approximate value of V_f, provided the specimen is homogeneous, i.e. that the cross section does not vary too much within the gauge length. Fig. 2 shows SEM images of the cross-sections of CFRP strands with fiber volume fraction of 45% and 71% where inter-fiber distances can be estimated. In this way it is possible to prepare CFRP specimens with different contact characteristics of the embedded fibers [12].

Table 1
Properties of Carbon fiber epoxy systems (based on manufacturer data sheets).

Fiber/epoxy grade	Filament number	Filament diameter (μm)	Density (g/cm^3)	Tensile strength (MPa)	Young's modulus (GPa)	Ultimate elongation (%)	Electrical resistivity (Ω. cm)
Toho Tenax HM35	12000	6.7	1.79	3240	345	0.9	1.0 × 10−3
Grafil Pyrofil TRS50	12000	7	1.82	4900	240	2	N/A
LM E20	–	–	T_g (°C) 70-95	70	3	4 to 6	N/A