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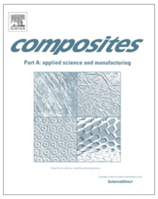

Aging of a polymer core composite conductor: Mechanical properties and residual stresses

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ABSTRACT

Polymer core composite conductor specimens were aged in atmospheric conditions at 140 and 180 °C and then tested under four point bending. When aged up to a year at a temperature of 140 °C no detrimental effect on flexural performance of the composite was observed, as opposed to aging at 180 °C, which had a very negative effect on the properties. A finite element model was developed to characterize the residual stress in the composite on a micro scale using representative volume elements (RVE). The residual stresses developed after aging at 140 °C for a year were minimal. However, at temperatures higher than 160 °C significant increases in the stresses were observed. The effect of chemical aging on the failure process of the rods was not considered but could result in the rapid reduction in the loads at failure for the rods tested at 180 °C for up to a year.

1. Introduction

The use of polymer matrix composites (PMC) in industrial applications has increased due to their lightweight yet desirable mechanical properties. However, in industrial applications, design life is of paramount importance. Many service environments can be harsh, which can lead to reliability issues of the material. This creates interesting and complex challenges to overcome which include not just the initial mechanical and material properties, such as mass loss and volumetric shrinkage of the PMC, but also the degradation of properties over time due to in-service aging conditions. Therefore the performance of aged PMCs is as important as knowing the unaged performance of the material. For PMCs, the matrix is the most susceptible to aging, especially in applications of long term high temperature exposure [1].

High voltage (HV) electric power transmission lines are an example of one such application. Polymer core composite conductors (PCCCs) are an alternative to the current transmission line technology (Fig. 1). PCCCs consist of a unidirectional carbon fiber composite (CFC) rod coated with an electrically insulating and corrosion resistant (ECR) glass fiber composite (GFC) layer and surrounded by trapezoidal shaped aluminum alloy strands which conduct the current. The load bearing hybrid composite has several benefits [1–3], but essentially the design allows for a greater amount of power to be transmitted in the same diameter line. This is due in part to the fact that PCCCs are not restricted to temperatures of approximately 100 °C as is the case with current transmission lines. Aluminum conducting steel reinforced (ACSR) transmission lines are temperature limited because they will sag significantly, a problem carbon fiber helps mitigate in the PCCC [4] due to a negative coefficient of thermal expansion in the axial direction. However, at these higher allowable operating temperatures, performance of the hybrid composite rod, and more specifically the matrix, will degrade over time due to aging.

Polymers, that are normally cooled to below the glass transition temperature (T_g), are not in thermodynamic equilibrium. This produces free-volume in the polymer, and over time at temperature, the polymer chains will reconfigure to reduce the free-volume thereby approaching equilibrium in a process called physical aging [5]. Aging in general, not just physical, will result in mass loss [1,6–11]. It was observed by Gentz that this volumetric relaxation was greatly influenced by the environment and temperature [6]. It has been theorized that the volumetric shrinkage associated with aging will increase internal stresses in the composite, thereby affecting the PMC's performance [4].

Burks et al. showed the effect of aging on fatigue life of a PCCC. It was concluded that after aging at 180 °C for 12 months, the volumetric shrinkage was creating enough matrix damage, and fiber/matrix interfacial damage hindering load transfer, to significantly reduce fatigue performance [4]. In another study, Burks utilized micromechanics via representative volume element

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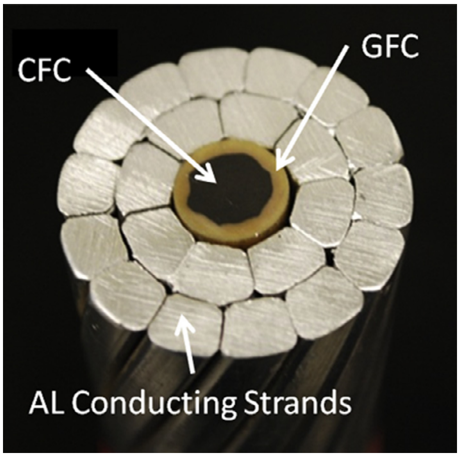

Fig. 1. An example of a PCCC used in next generation power transmission lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(RVE) modeling to show the stress distribution in the matrix due to Aeolian vibrations as a function of aging time. Burks showed that on a micro scale, the matrix was in a higher state of stress in the GFC than in the CFC. It was also shown that the maximum stress in the matrix was exacerbated with aging time [12].

The Burks study [12] did not deal with stress distribution within the matrix when subjected to the temperature at which it is aged, nor was the volumetric shrinkage associated with each aging temperature considered. Therefore the goals of this study are: to characterize the flexural performance of the hybrid composite rods, to determine the residual stresses within the epoxy matrix due to aging using micromechanics while considering volumetric shrinkage, and to determine the activation energy of the physical aging process of the epoxy matrix.

2. Experimental

2.1. Materials and specimen preparation

An in-depth description of the material and preparation for the neat resin can be found in a previous study [1], but is briefly summarized here for completeness: a cycloaliphatic high temperature (HT) epoxy resin mixed with a nadic methyl anhydride hardener was used. The monomer, Lindoxy-190, and hardener (LS-252) were supplied by Lindau Chemicals Inc. (Lindau). Specimen manufacturing was done at Composite Technology Development (CTD) in Lafayette, Colorado where the neat resin was first mixed, and then degassed for four hours. After mixing, the resin was cured in a 6.35 mm thick mold using a three step cure cycle established by Lindau, then cut using a diamond wafering blade to approximately 12.7 mm length, and 6.35 mm width.

The cores of the PCCCs that were studied were unidirectional hybrid composite rods that contained a T700 carbon fiber composite surrounded by an electrically insulating ECR-glass fiber composite. The matrix of both composites is also a cycloaliphatic HT epoxy resin. However, the exact source of the resin was not made available to this project. The volume fractions of fiber were 64% in the GFC portion and 69%, in the CFC portion [13]. The hybrid composite rods were supplied by the Western Area Power Administration (WAPA). It was concluded in [1] that the cycloaliphatic epoxy/NMA hardener manufactured in this study and the epoxy system used in both the CFC and GFC sections of the rods were most likely the same or very similar polymers.

3. Experimental methods

3.1. Aging of hybrid composite rods

The hybrid composite rods were aged in atmospheric conditions at 140 °C and 180 °C. These temperature conditions were chosen to simulate accelerated aging below the glass transition temperature, which is about 205 °C. The specimens were cut to a length of 355.6 mm using a diamond blade chop saw with the ends of the composite rods sealed with a silicone thermal sealant to prevent axial thermo-oxidation. After aging the rods were cut to their final test length of 279.4 mm. For each temperature specimens were aged for 3, 6, 9 and 12 months in a Precision Scientific EconoTherm Laboratory Oven.

3.2. Aging of neat resin

The neat resin specimens were manufactured at Composite Technology Development (CTD) in Lafayette, Colorado. An in-depth description of the manufacturing and curing of the epoxy can be found in [1], but briefly the neat resin was mixed for 2 min at 198 RPM, degassed for four hours at an average vacuum of 23 Pa, and then cured. The cure cycle used was established by Lindau but can be found in [1]. After curing, the specimens were cut using a Buehler ISOMET 1000 diamond saw to dimensions that follow ASTM Standard D 790-07. The dimensions were 60.96 mm long, 3.175 mm thick and 12.7 mm wide. The inner span of the test fixture was 50.8 mm, which allowed the specimens to have an overhang of 10% [14].

3.3. Flexure testing

The neat resin flexure tests followed the ASTM Standard D 790-07 [14], and were performed in displacement control with a loading rate of 1.346 mm/min. The specimens were loaded and set square after the loading pins were first aligned. Before each test, 1 N of preload was applied to each specimen.

Eq. (1) shows how the flexural modulus (E) was calculated [14]

$$E = \frac{L^3 m}{4bd^3} \quad (1)$$

where L is the support span, m is the slope of the linear portion of the load vs displacement curve, b is the width of the beam tested, and d is the depth of the beam tested.

The four point bend test configuration developed by Burks et al. was used to test the flexural strength of the hybrid composite rods after aging. The tests were performed in displacement control (Fig. 2) with a loading rate of 3 mm/min on an MTS 858

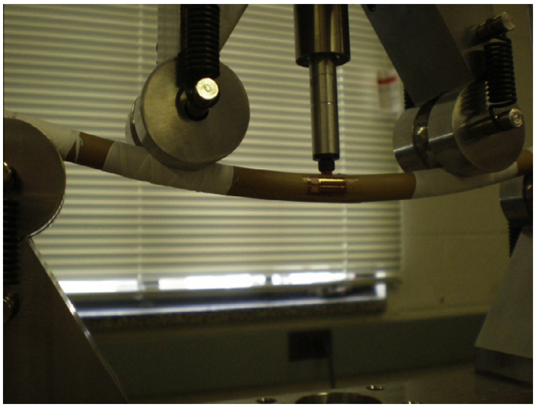

Fig. 2. The four point bend test setup used for flexure tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)