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Material properties

Effects of accelerated aging on mechanical, thermal and morphological behavior of polyurethane/epoxy/fiberglass composites

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ABSTRACT

Wind blades, an important application of polymeric composite materials, are subject to natural weathering. This study aims to evaluate mechanical, thermal and morphological behavior during accelerated aging in three thicknesses of epoxy and fiberglass polyurethane-coated composite plates used in wind turbines, in addition to testing with two acoustic emission techniques. An accelerated aging chamber simulated natural weathering mechanisms for 45, 90, 135 and 180 days. This degradation primarily reduced the mechanical properties of the thinner composites, with some damaged specimens exhibiting fiber-matrix debonding. Thermal properties deteriorated. There were no morphological changes on the polyurethane–epoxy interface; however, degradation occurred in the fiber-matrix interface on the surface exposed to radiation. The degree of chalking indicated coating deterioration on the external surface of the polyurethane. The acoustic wave propagation speed and attenuation coefficient measured prior to mechanical testing indicated the presence of damage areas.

1. Introduction

In recent decades, there has been a growing demand to exploit global wind potential, transforming wind blades into one of the most important applications of polymeric composite materials. Some wind turbine components, primarily wind blades, are manufactured using polymeric composite materials [1–4]. Chemical or environmental aging is caused by various agents, such as humidity, loading conditions and ultraviolet radiation (UV), leading to irreversible changes in the molecular structure of these materials [5–7]. The polymeric matrix is usually more susceptible to aging and generally controls the long-term performance of the composite [5,6]. The critical portion of UV radiation causes photo initiation of the polymer due to the absorption of chromophores present in the matrix (hydroperoxides, catalyst residues, carbonyls, unsaturation). Excited chromophores induce photooxidative decomposition of macromolecular chains, leading to basic behavior changes in the polymer and its properties. Photoinduced processes usually change the appearance (surface gloss, color) and mechanical properties (strength, strain, flexibility) of the polymer [8,9]. The combined action of all these factors on the behavior and durability of composites is a highly complex phenomenon that occurs at the molecular level.

When a polymer is subjected to ultraviolet radiation it releases constituents in the form of thin, loosely adherent dust. This coating defect is called chalking [10,11]. Coatings are expected to be durable and retain their properties over time. As such, resistance to light, humidity and temperature is a general requirement. The environmental impact of coatings can be further reduced by increasing their efficiency and useful life. The most common cause of coating degradation is ambient exposure to ultraviolet (UV) radiation, water/humidity and temperature fluctuation. In many cases, degradation is evaluated based on changes in chemical structure and the presence of foreign chemicals in the system as a function of time. Polyurethane coatings made with an aliphatic and cycloaliphatic isocyanate-based curing agent exhibit excellent resistance to ultraviolet rays as well as good color retention and glow when exposed to natural weathering. Furthermore, they show good resistance to chalking [12].

A controlled artificial weathering test should replicate

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conditions typically found in the natural aging process through cycles representing day and night, and periods of surface drying and wetting. The advantage of this method is the ability to accelerate the testing of all controlled parameters, obtaining comparable results at significantly lower exposure times [13].

Possible causes of failures in composite materials used to manufacture wind turbines are an abrupt change in blade thickness with tension concentrators and decoupling of the resins or delamination. Decoupling resins may also be associated with processing defects in manual lamination. Both the individual and collective action of these defects can cause premature wind blade failure [14]. Debonding of the outer skin was the initial failure mechanism, followed by delamination buckling which led to the blade's collapse [15]. Tests using a full-scale wind turbine blade to study structural fatigue behavior are costly, and hence few studies have been conducted to date [15]. Another approach to improve the reliability of wind turbine blades is to evaluate the mechanical properties of composite laminates. Non-destructive testing, such as acoustic emission (AE), is one of the most appropriate to characterize composite materials. AEs are transient ultrasonic waves generated by sudden movement in material under stress [16–18]. When a component is subjected to mechanical load, discontinuities in materials may release AE energy. The electrical signals are then amplified and further processed as AE signal data. Accurate processing of the AE signals can identify different damage mechanisms in composites [19,20].

Therefore, the present study aims to evaluate the mechanical, morphological and thermal properties of artificially degraded composite plates. The properties identified in different analyses provide knowledge on the durability and structural applications of composites exposed to environmental conditions. The signals obtained from acoustic emission provide information on the formation of discontinuities or voids arising from degradation.

2. Experimental

2.1. Materials

Composite plates (1, 3 and 6 mm thick) manufactured by hand lay-up were used. These consist of 989 Biax Saertex 45°/-45° fiberglass fabric layers, Hexion R1M135 + 1366 epoxy resin and DM Coating-sprayed polyurethane. For degradation cycles the plates were machined according to the tensile test specimen (ASTM D638) and Izod impact specimen (ASTM D256-10) [21,22].

2.2. Composite characterization

The effects of sunlight were simulated by a system of 8 UVB radiation sources in the 280–320 nm range using an UV-C Adexim-Conexim® accelerated aging chamber. Specimens were exposed to a UVB radiation cycle at 60 °C for 6 h, followed by exposure to 6 h of condensing water vapor at 50 °C and 100% humidity according to ASTM G154-06 [23] (Fig. 1). Specimens were removed every 1080 h (45 days) and four degradation conditions were evaluated: 45, 90, 135 and 180 days.

A Physical Acoustics Corporation® sensor (model ASP05F0021) was used for the acoustic emission test. A mechanical stimulus was provided by breaking graphite (Fig. 2), according to ASTM E976-10 and ASTM E1067-07 [24,25]. The absolute maximum and superposition methods were used.

2.2.1. Absolute maximum method

The maximum peak time values of each sensor were associated with distance (x) to provide propagation speed. Acoustic signal attenuation (α), expressed in dB/m, was measured using attenuated acoustic intensity (I) and non-attenuated intensity (I_o), as described in Equation (1) [26]:

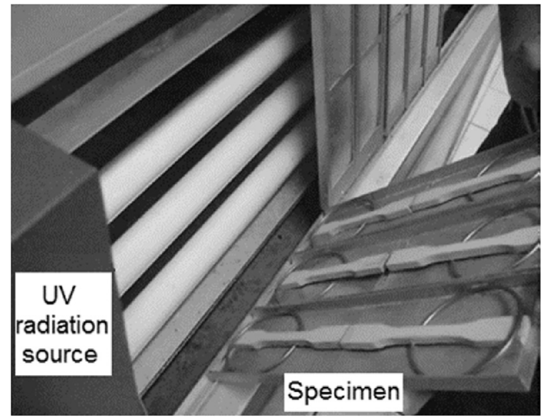

Fig. 1. Specimens in the accelerated degradation chamber.

$$I = Io \cdot e^{-\alpha x} \rightarrow \alpha = \frac{1}{x} \cdot \ln \frac{Io}{I} \tag{1}$$

2.2.2. Superposition or cross-correlation method

The time-of-flight (τ_0) of the acoustic wave between two adjacent signals $B_1(t)$ and $B_2(t + \tau_0)$, can be used to determine the wave speed through the specimen. Thus, propagation speed can be determined with τ_0 and the distance between sensors [27,28]. Time-of-flight was estimated by the cross-correlation or superposition method. The value of τ_0 is computed as the value of τ, which is maximum in Equation (2):

$$\left| \int_{-\infty}^{\infty} B_1(t) \cdot B_2(t - \tau) dt \right| \tag{2}$$

The cross-correlation of two functions (B_1 and B_2) involves shifting B_2 in τ toward B_1 and multiplying them to determine for which value of τ (τ_0) the product is maximized. This means that the maximum of the integral of the cross-correlation between echoes B_1 and B_2, as a function of time delay, corresponds to their maximum correlation [28].

An EMIC® DL 10000/700 universal testing machine with a 100 kN load capacity was used for tensile testing. The deformation rate was 50 mm/min. Composite plates were tested by Izod impact testing in each degradation condition according to ASTM D256-10 [22]. According to this standard, the minimum thickness is 3 mm. A CEAST® Resil 5.5, 5.5 J test hammer and impact velocity of 3.46 m/s were used in this test, with a type B, V-shaped notch and a 45° angle.

Thermogravimetric analysis (TGA Q 50®) was carried out at temperatures ranging from 25 °C to 800 °C in air, with a heating rate of 10 °C min^{-1} and flow rate of 100 mL min^{-1}, using about 10 mg for each sample. Differential Scanning Calorimetry (DSC Q 20®) was employed to determine the glass transition temperature (Tg) of the composites. A heating rate of 10 °C/min at −50 °C to 500 °C was applied to 10 mg samples under nitrogen.

The sample constituents and their interfaces were viewed under an Olympus optical microscope (model BX 51 M) at magnifications of 50×, 100×, 200×, 500× and 1000×. Cross-sections were made for sample preparation using a water jet cutter and water-only cutting, followed by sanding with 300, 600 and 1200 grit sandpaper, and mechanical polishing with diamond paste. Both procedures were performed using a Teclago® PL 02 polishing machine.

The polyurethane coating was directly exposed to UVB radiation