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Effect of fibre straightness and sizing in carbon fibre reinforced powder epoxy composites

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ABSTRACT

Carbon fibres with three different sizing agents were used to manufacture unidirectional composites based on powder epoxy resin. A specially designed tensioning apparatus was adopted to apply tension on fibres during the thermal curing cycle, in order to achieve an enhancement of fibre straightness. Chemical composition and surface morphologies of the carbon fibres were extensively characterised. The composites were evaluated using tensile, flexural and interlaminar shear strength tests, and mechanical performance measured based on fibre orientation, fracture modes and interfacial properties. The results demonstrated that composites processed with fibres under tension resulted in an increased unidirectional character in connection with the different amounts of sizing. Flexural and interlaminar testing of the laminates, in addition to Scanning Electron Microscopy and Dynamic Mechanical Thermal Analyses, revealed interfacial adhesion differences, emphasizing the importance of the adequate combination of the polymeric matrix and the type of reinforcement to the structural integrity of composite.

1. Introduction

Epoxy resins (thermoset polymers) are of significant importance to the engineering field with fibre-reinforced epoxies being applied widely in the aeronautics, automotive, marine and renewable energy industries [1–7]. Epoxies are characterised by high stiffness, excellent chemical and corrosion resistance, high thermal and mechanical properties, exceptional adhesion to numerous substrates, low shrinkage during cure, outstanding electrical insulating properties, and the good processing ability under various conditions [4,8–11]. The extensive use of epoxy thermosets in several high potential applications is restricted, however, by their inherent fracture toughness limitations, leading to brittleness, and delamination failures [8,12,13]. In the coating industry, powdered thermosets have been widely adopted, rather than conventional epoxy systems, due to the emission of zero, or near zero, volatile organic compounds (VOC), the absence of solvents, and the potential for extensive utilization as well as economical and environmentally friendly properties i.e. disposability and less hazardous wastes [14,15]. The most robust advantages of the powder epoxies are the characteristically low exothermic reaction during curing process compared to the conventional systems and the ability of the powder to melt, and flow, at elevated temperatures without significantly increasing the degree of cure [16,17]. Utilising the unique properties of the epoxy powders, improvements in the quality and uniformity of the cured material can be achieved with the use of powder epoxy resin, while also reducing the final production cost. These meaningful processing properties have attracted the interest of tidal and wind industries where the need of manufacturing thick-section composite structures is required e.g. turbine blades or root spars [18].

It is well-known that the fracture characteristics of carbon fibre reinforced polymers (CFRPs) are affected by a lot of factors including properties of raw materials, fibre content, orientation and straightness, voids, moisture, temperature and manufacturing processes. However, the ultimate performance of the composite is not only determined by the involved phases, but is also influenced to a large extent by the interphase formed between the two components [19–21]. Considering that the compatibility between the carbon fibres and resin matrix is one of the most fundamental parameters that controls effectively the properties of the composite, it is therefore necessary to research the interphase phenomena providing valuable insight for industry applications.

The interfacial bonding between the fibres and the polymer matrix is expected to be dependent on the surface properties of the fibre such as roughness, porosity and functional groups, on the chemical character

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of the matrix [19,22,23], on the presence of defects (voids, low cohesion) [19] and on residual thermal stresses [24]. The sizing materials (usually a thin polymeric coating applied on the surface of unsized carbon fibres [25,26] in low concentrations i.e. 0.3–1.5 wt.%, protect the brittle fibres from damage and improve the processability and structural integrity of the composite, alter the manner that the stress is transferred from the matrix to the fibres as well as promoting interface bonding performance [9,19,23]. In addition, the sizing agent can change the apparent surface energy of the carbon fibre, the wetting ability and the physicochemical interactions with the epoxy matrices [27,28].

Manufacturing processes of FRPs involve the selection of appropriate materials, design ideas and fabrication techniques. Among the different fabrication processes, pultrusion is recognised as one of the most cost-effective and energy-efficient processes due to its high automation and great production rates [29–31]. The combination of pulling and extrusion methods adopted by this technique can deliver superior performance composites characterised by high fibre volumes as high as 70% and in turn enhancing the stiffness profile of the material [29]. Moreover, improvements in FRP properties have been found during pultrusion, as the fibres are pulled under tension in a continuous form resulting in exceptionally high straightness characteristics [29,32]. Recently, there is growing interest in the renewable energy industry for the use of pultruded sections or planks in the spar caps of very long (> 60 m) wind turbine blades, as well as for innovative vertical axis wind turbine blades (VAWT) [33,34].

The main aim of the present investigation is to gain a better understanding of the mechanical properties of powder-epoxy resin composites reinforced with UD carbon fibres for manufacturing out-of-autoclave components. The key challenge of the work was to demonstrate the effect of the type of sizing on the fibre surface, in conjunction with fibre straightness, on the mechanical performance of the laminates. A novel hand lay-up process was employed to manufacture powder-epoxy composites reinforced with three different types of carbon fibres. The fibre volume fraction, the void content and the fibre orientation of the composites were experimentally measured and compared to optical methods. Mechanical properties in terms of tensile, flexural, and interlaminar shear strength along with the optical characteristics of the tested/failed composite samples were evaluated. The understanding of the factors controlling and driving the dominant failure modes was an objective as well. Furthermore, the influence of fibre/matrix interphase on interfacial adhesion has been investigated through tensile, flexural properties and interlaminar strength connected with the carbon fibre surface roughness and sizing functional groups.

2. Experimental procedure

2.1. Materials and composite preparation

Commercially available continuous tow carbon fibres T700S-24K-50C (1% sizing agent), T700S-24K-F0E (0.7% sizing agent) and T700S-24K-60E (0.3% sizing agent) from TORAYCA® (Toray Industries, Inc.), were used in the present work. Powder epoxy resin (EC-CEP-0016) supplied from EireComposites Teo. with density 1.22 g/cm^3, was used as the matrix to manufacture the composite materials. The powder-epoxy used has recently been investigated by Maguire et al., using characterisation techniques and a modelling methodology under various processing conditions, and proposed as a new high-quality, cost-effective alternative of manufacturing out-of-autoclave components for marine applications [16,35].

All initiators-reagents were mixed in the powder, the curing reaction was heat-activated and the supplier recommended a cure temperature at ~180 °C. Unidirectional carbon fibre powder epoxy composite (CFRP) plates with dimensions of 450 × 250 mm (length × width) and thicknesses of ~1 mm (5-plies) and ~3 mm (15-plies), were fabricated, respectively. Fig. 1(a) shows a representative image of the composite's lay-up i.e. the taped carbon fibres and the deposited powder epoxy (white material). Moreover, a novel hand lay-up process which used a specially designed tensioning apparatus was adopted such that the carbon fibres were kept in tension during the cure process, targeting an enhancement of fibre-straightness, see Fig. 1(b). Carbon fibre tows were cut to the desired length and laid side by side on a flat surface. The fibre tows were combed by hand to align any loose fibres and smooth the appearance of the tows. The taped fibres (plies) were loaded in the tensioning apparatus, Fig. 1(b), clamped at both ends and then tension of around 3000 N was applied uniformly until fibres started sliding at both clamped ends. Note that the applied tension on the carbon fibre plies was estimated with two techniques by using a Newtonmeter and a torque wrench. A mass of ~300 Kg was applied uniformly on the fibre plies which was equalled to ~3000 N according the Newtonmeter readings. Also, a torque wrench was employed and the tightness of the screws that were helping to apply tension (extend the carbon fibres plies) was estimated. The measured value using the torque wrench revealed force values of the same order of magnitude as with the Newtonmeter. However, this technique suffers from inaccuracy due to inconsistent or uncalibrated friction between the fasteners and used the screw-bar. The epoxy powder was distributed evenly on each ply aiming towards a 60:40 (carbon: epoxy) final weight ratio of the laminate. The thickness of a single ply was approximately 0.2 mm. Fig. 1(c) present a typical image of a final CF/epoxy composite laminate with thickness of 1 mm (5 plies).

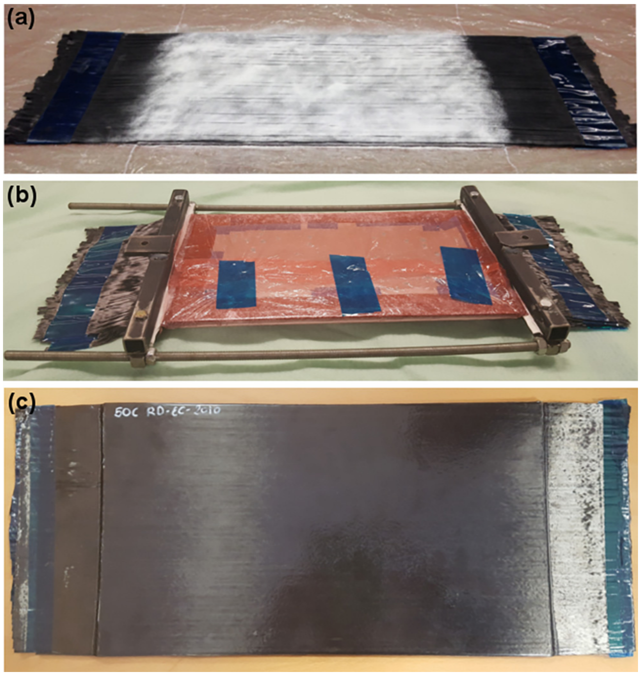

Fig. 1. Typical images of the (a) carbon fibre (black) powder epoxy (white) lay-up with no tension (b) apparatus used to apply tension on the fibres during the thermal cycle and (c) manufactured carbon fibre epoxy composite laminate. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The thermal cycle applied to all the laminates (tensioned and non-tensioned) consisted of a drying stage; an isothermal dwell at 50 ± 1 °C for 400 min, B stage; isothermal dwell at ~120 ± 1 °C for 60 min and a curing cycle with a heating rate of 2 ± 0.2 °C/min up to 180 ± 1 °C, holding at this temperature at least 90 min, followed by cooling down to room temperature. The fabrication process was under vacuum conditions. All samples were consolidated by vacuum, and breather cloth was employed to remove the air bubbles and volatiles. The test coupons of all T700S/epoxy composite laminates were cut using a diamond saw (wet) technique to produce high quality smooth

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