Composites: Part A 84 (2016) 299–307

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Effect of CNTs addition on the erosive wear response of epoxy resin and carbon fibre composites

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ARTICLE INFO

Article history:
Received 11 September 2015
Received in revised form 3 February 2016
Accepted 13 February 2016
Available online 19 February 2016

Keywords:
A. Nanocomposites
A. Hybrid
A. Carbon nanotubes
B. Wear

ABSTRACT

In the current study we investigated the effect of carbon nanotubes (CNTs) addition on the erosive wear response of epoxy resin and carbon fibre reinforced laminates (CFRPs) and demonstrated the positive synergy of CNTs and carbon fibres, which resulted in almost 50% decrease of the erosion rate (ER) of the CFRPs at high impact angles (90°). Incorporation of CNTs led in slight increase of the ER of the epoxy systems, especially at low impact angles. The relative fibre orientation in the CFRPs had a negligible effect on the erosive wear response mainly due to the quasi isotropic nature of the tested CFRPs. Based on the erosion efficiency parameter the response of the epoxy systems was characterised as semi-brittle, while CFRPs behaved in a brittle manner. Scanning electron micrograph provided evidence that the presence of CNTs reduced the amount of broken and/or detached fibres in the case of CFRPs.

1. Introduction

During the last decades, carbon fibre reinforced composites (CFRP) with improved mechanical properties, are continuously displacing more conventional materials, such as aluminium and titanium alloys, for primary aircraft structures. State of the art commercial aircrafts such as the Boeing 787 and the new Airbus A350XWB confirmed earlier studies which estimated composite usage for aircrafts at higher than 50% of their structural mass [1]. Furthermore, the idea to combine CNTs with conventional CFRPs, has attracted much attention during the last decade as they have been proven to provide additional functionalities such as sensing [2–4] and damage monitoring [5,6]. Mechanical and damage tolerance enhancement have also been observed [7–9]. An increase of ca. 50% in Mode I and 75% in mode II fracture energy for hybrid carbon fibre composites reinforced with 0.5% CNTs has been reported [10]. Along with the intensive characterisation of the mechanical response of CNTs modified epoxies, the tribological response of such systems has been recently examined [11–19]. Owing to their excellent mechanical and thermal performance as well as self-lubricating effect of the CNTs it has been anticipated that their addition would lead into considerable reduction in the coefficient of friction and wear rate of the nanomodified systems. Although improvement in the wear resistance has been reported, it has been documented that this is being limited by insufficient dispersion and agglomeration of the CNTs in the epoxy matrix. To overcome dispersion issues reinforcement in the form of buckypaper, surface modification or CNT alignment, have been recently proposed [17–19].

While the tribological performance and abrasive wear of CNT modified epoxies has received considerable attention, limited information exists on the effect of the nanofiller on the erosive wear response of polymeric systems [20–23]. This wear mode arises from the repeated impact of solid and sharp airborne particles on a solid surface. Numerous studies have been published on the solid particle erosion of polymer composites discussing mainly the effect of test parameters (erodent type and size, impingement angle, impact velocity, flux rate), and composite characteristics (fibre content, weave style, stacking sequence, interleaves, fibre/-matrix adhesion, relative fibre orientation with respect to erodent flow direction) [24–27]. Attempts have been made to correlate the erosion behaviour with the physical and mechanical properties (hardness, tensile-strength and -modulus of elasticity, fracture toughness, yield stress and yield strain, rebound resilience, friction coefficient, ultimate strength and strain, etc.) of the investigated systems with limited success, due to the fact that the material removal is dependent on many interrelated factors, the combination of which sometimes exceeds 20 in number [24].

The addition of CNTs is anticipated to increase the complexity and alter the erosive wear response of the nanomodified composites, since it greatly influences fracture toughness, energy dissipation and damping characteristics of such systems. Thus, the characterisation of the erosive wear response of CNT modified

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http://dx.doi.org/10.1016/j.compositesa.2016.02.012
1359-835X/

systems is of critical importance in order to qualify them as appropriate alternatives of traditional composites. This is of primary importance in dusty environments where solid particle erosion is a severe problem e.g. during operation of aircraft structures and engines over dusty terrains [22]. Specifically, based on the two very recent publications found on the erosive wear response of CNTs modified epoxies [22,23] it was demonstrated that CNTs addition was in general beneficial for the erosion resistance of the investigated systems with the erosive wear performance being strongly dependent on the alignment geometries of CNTs in respect to the particle stream.

Since limited information exists on the effect of CNTs addition on the erosive wear response of epoxies and CFRPs, the current study focuses on the characterisation of the erosive wear response of such systems. As aforementioned, for improved performance of the nanomodified systems CNTs dispersion is of crucial importance. In previous studies we have investigated the effect of sonication parameters (sonication duration and amplitude) on the macroscopic mechanical, thermomechanical, toughness response and durability of CNTs modified epoxies and CFRPs [28,29]. Optimal results were obtained for intermediate levels of sonication duration and amplitude, which allowed appropriate dispersion without damaging the CNTs structure. Based on these results we employed an optimised sonication protocol in order to incorporate 0.5 wt% CNTs which were uniformly distributed in the epoxy resin and used as matrix to create hybrid CFRPs (designated as doped systems). For comparison reasons, unmodified epoxies and CFRPs were also prepared (designated as neat systems). All materials were exposed to solid particle erosion at three impact angles (30°, 60° and 90°). For the neat and doped CFRPs the influence of the relative fibre orientation (parallel and perpendicular to the particle flux) was also assessed. The surface topography of the eroded composites was investigated by a scanning electron microscope (SEM) in order to obtain insight into the erosive wear mechanism as a function of the testing conditions and materials characteristics.

2. Experimental

2.1. Materials

The Graphistrength Multi Wall CNTs supplied by ARKEMA, France were used in this study. The tube diameter ranged from 10 to 15 nm, the tube length ranged from 500 nm to 1 μm. The production method of the nanoparticles was Catalyzed Chemical Vapor Deposition (CVD). A two part low viscosity epoxy resin, i.e. Araldite LY 564 and Aradur 2954, supplied by Huntsman Advanced Materials, Switzerland at a mix ratio of 100:35 by weight was used as matrix. For the 16 plies quasi isotropic laminates CFRPs, the G0947 1040 unidirectional carbon fabric by Hexcel (France) was employed as reinforcement.

2.2. Specimen preparation

The UP400S ultrasonic mixer (Hielscher) was used to disperse the CNTs into the epoxy resin. CNTs and Araldite LY 564 resin were weighed according to the w/w provided by the manufacturer and mixed together in a beaker. A high intensity ultrasonic probe was employed for the mixing process. The temperature of the mixture was kept low by submerging the container in an ice bath [30]. Based on a previous study an optimized sonication protocol was followed (50% amplitude, for 2 h) [28,29]. The amplitude percentage corresponds to a maximum sonotrode power of 400 W at 24 kHz frequency. Once the sonication was complete, the hardener was added to the modified resin and mixed using a mechanical agitator for about 10 min. To remove entrapped air and voids induced during mixing [31], the mixture was degassed in vacuum for 10 min. Finally, the mixture was transferred to open silicone rubber moulds and cured for 2 h at 60 °C, as recommended by the supplier. As demonstrated in the SEM micrograph of the doped epoxy resin, shown in Fig. 1, a uniform dispersion of CNTs was obtained following the aforementioned sonication protocol. CNT modified epoxy as well as unmodified epoxy resin were employed as matrix for the manufacturing of 16 plies quasi isotropic laminates CFRPs, $[0/45/-45/90]_{s2}$. The CFRPs were manufactured with the hand layup method and pressed in a heated hydraulic press under the pressure of 100 bars at temperature of 60 °C for 2 h. All specimens were post-cured at 120 °C for 4 h.

2.3. Erosion chamber

All erosion tests were performed in a commercial sand-blasting chamber (M110/DC600, Neodynamiki, Aspropyrgos, Greece). The equipment was modified according to the ASTM G76 83 standard [32]. Sharp, angular aluminium oxide (Al_2O_3) particles with a size between 177 and 250 μm were selected as the erodent. The distance between the sample holder and the nozzle was constant (180 mm). The impact angle was adjusted by turning the sample holder at three different angles of impingement (30°, 60° and 90°). A particle velocity of 38 m/s, calculated using the double slat disk calibration method [33], was obtained using 4 bars air pressure in the nozzle. The mass flow of the erodent material perpendicular to the flow axis was 6.15 g/s. All erosion tests were performed at room temperature until steady state erosion was reached. At least three specimens were tested per experimental condition. The weight loss was recorded as a function of erosion time by a precision balance (220 g maximum load with accuracy 0.1 mg). Before weighting, the Al_2O_3 particles were removed from the specimen surface by air blasting. The erosive wear behaviour was characterised using the erosion rate (ER) of the specimen defined through the weight loss rate (mg/kg), i.e. the weight loss of the specimen due to erosion normalised by the weight of the erodent causing the loss. In order to investigate the effect of the relative fibre orientation in respect to the erodent flux, CFRPs specimens were positioned so that the flux was parallel (Pa) or perpendicular (Pe) to the 0° ply of the laminate. Detailed illustration of the definition of the Pa and Pe direction of the erodent flux in respect to the fibre orientation can be found in [34].

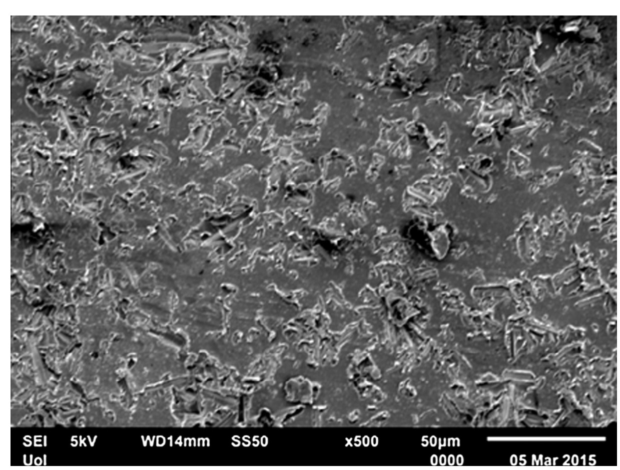

Fig. 1. SEM micrograph demonstrating the dispersion level of CNTs in modified epoxy resin.