Composites Part B 110 (2017) 396–401

Contents lists available at ScienceDirect

Composites Part B

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

Enhancement on mechanical strength of adhesively-bonded composite lap joints at cryogenic environment using coiled carbon nanotubes

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ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form
6 November 2016
Accepted 9 November 2016
Available online 11 November 2016

Keywords:
Nano-structures
Polymer-matrix composites (PMCs)
Adhesion
Mechanical properties

ABSTRACT

The hardness, tensile and lap joint shear behaviors of pure epoxy, straight multi-walled carbon nanotube (MWNT)/epoxy and coiled multi-walled carbon nanotube (CCNT)/epoxy adhesives conditioned at room temperature (RT) and cryogenic temperature (CT) were investigated in the present study. Experimental results showed that all adhesives had greater Vickers hardness values, Young's moduli and tensile strengths at CT. The performance of CCNT/epoxy adhesive at CT was outstanding due to the enhancement of mechanical interlocking effect between CCNTs and epoxy at low temperature. This effect led to a greater Vickers hardness value, Young's modulus and lap joint shear strength of this adhesive at CT when compared with MWNT/epoxy type. The result from finite element analysis (FEA) also proved that the contraction of matrix at CT induced additional clamping force onto the surface of nanotubes. Due to the larger surface area of CCNTs, a relatively stronger bonding strength was achieved, and thus, CCNT/epoxy adhesive had better mechanical properties at low temperature condition.

1. Introduction

In recent years, the use of fiber reinforced polymer (FRP) composites in the aerospace engineering industry has been growing rapidly. To assemble these FRP structures, mechanical bonding methods such as fastening by bolts and nuts are currently used. However, there are many drawbacks for these methods. The metallic bolt and nuts are relatively heavy which contribute to the large amount of fuel use for modern aircraft. The undercuts for fasteners also lead to failure of composites since stress concentration will be developed around fastening joints. To solve these problems, the adhesive bonding method was suggested for FRP composite structures [1]. This method not only reduces the weight of aerospace structures, but also avoids the development of stress concentration and eliminates air gaps at the bonding area.

In fact, aerospace structures often encounter extremely low temperature conditions during their service. For example, spacecraft are servicing in the low earth orbit at a temperature down to −170°C [2]. FRP composites with adhesive bonding are also used in cryogenic fuel tanks which carry extremely low temperature fuels (−150°C or even lower) [3]. The mechanical behaviors of FRP composites at temperatures down to −60°C were studied by many researchers [4–6], but studies on cryogenic conditions (−150°C or lower) are still very limited. Epoxies are the most commonly-used adhesive for bonding FRP composites but they become brittle with low strength and fracture toughness at cryogenic conditions. Therefore, it is vital to enhance the mechanical behavior of epoxy adhesive for such circumstances.

In order to improve the mechanical strength of adhesively bonded lap joints at room temperature, researchers added nanofillers such as carbon nanotubes (CNTs) and nanoclay to an epoxy adhesive to form a new type of nanocomposite [7–9]. This method has been believed to effectively enhance the strength of the nanocomposite at extremely low temperature environments due to the mismatch of their coefficient of thermal expansion [10]. Owing to the high aspect ratio and extra-ordinary mechanical properties

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http://dx.doi.org/10.1016/j.compositesb.2016.11.019
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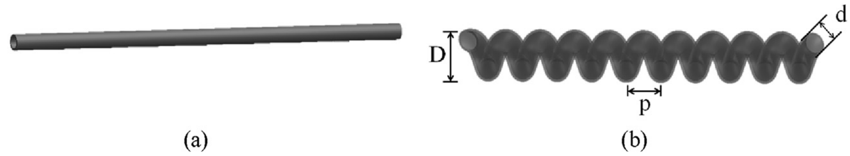

Fig. 1. Schematic diagrams of (a) a straight carbon nanotube and (b) a coiled carbon nanotube (CCNT).

of straight multi-walled carbon nanotubes (MWNTs), adding them into epoxies as nano-reinforcement can enhance their mechanical properties. However, since the interfacial bonding strength between MWNTs and polymer is weak, the enhancement was not always very significant [11–13].

To tackle the aforementioned problem, coiled multi-walled carbon nanotubes (CCNTs) was proposed to be nano-reinforcements for nanocomposites [14]. CCNTs are carbon nanotubes with a helical configuration, like springs. The strength enhancement effectiveness of nanocomposites is governed by the diameter of CCNT (d), the diameter of coil (D) and coil pitch (p). Fig. 1(a) and (b) illustrate the difference between a straight CNT and a CCNT. Previous studies have provided strong evidences that CCNTs can enhance the interfacial bonding properties and thus the mechanical properties of polymer-based composites. CCNT/epoxy composites were found to have a more compact interface than straight single-walled carbon nanotube (SWNT)/epoxy and straight multi-walled carbon nanotube (MWNT)/epoxy composites due to the existence of mechanical interlocking between the CCNT and surrounding matrix [14,15]. The present study aims at investigating the hardness and tensile behavior of CCNT/epoxy nanocomposites and also the lap joint shear strength of this nanocomposite adhesive at cryogenic condition by comparing them with pure epoxy and MWNT/epoxy adhesives, to explore the feasibility of using CCNT/epoxy adhesive for aerospace engineering applications.

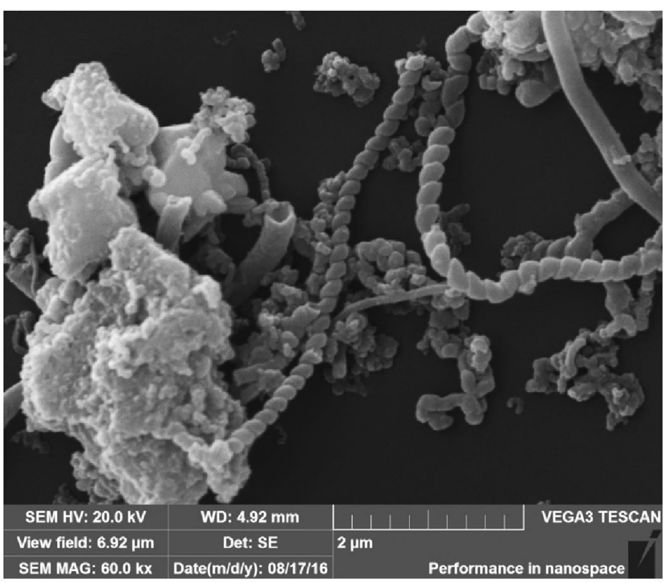

Fig. 2. SEM image of CCNTs.

2. Experimental

2.1. The nano-fillers

MWNTs used in the current study were purchased from Shenzhen Nanotech Port Co. Ltd. The outer diameter was 10–20 nm while the length was around 5 μm. CCNTs were produced by catalytic chemical vapor deposition (CCVD) in Shanghai Maritime University. Scanning electron microscopy (SEM), Tescan Vega3, was used to examine the CCNTs to study their geometry. Fig. 2 shows an SEM image of CCNTs. The coil diameter (D) and coil pitch (p) are both around 200 nm. The length of each CCNT is around 5 μm which is similar to that of the MWNTs used in this study.

2.2. Sample preparation

The nanocomposite samples for Vickers hardness test and tensile test were prepared according to the method reported by Lau et al. [4]. Araldite GY251 Epoxy and HY956 Hardener were used as the matrix of all the samples in the current study. All samples contained 1% of carbon nanotubes by weight. They were molded into different shapes according to the standard ASTM E384 (Vickers Hardness test) and ASTM D638 (type IV) (tensile property test). Pure epoxy samples were also prepared by the same route for comparison.

The samples for lap joint shear test were manufactured according to the standard ASTM D5868 and ASTM D1002. The adherent, woven glass fiber/epoxy composites, was prepared by

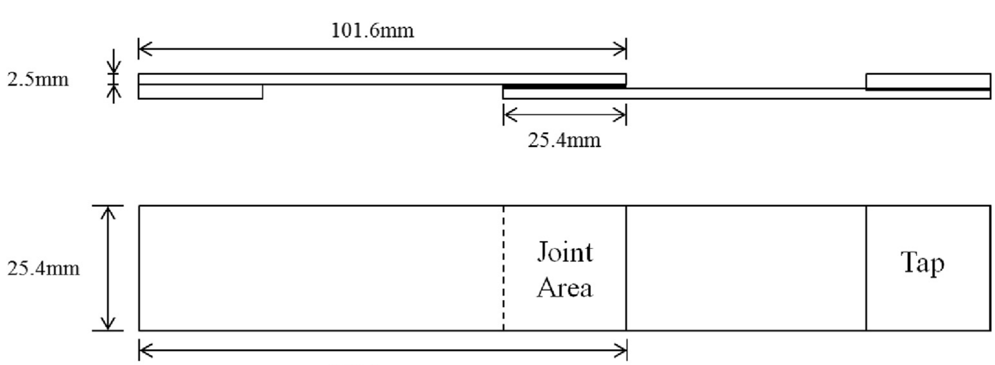

Fig. 3. Schematic diagrams of a lap joint shear test sample.