WOVEN CARBON FIBER EPOXY COMPOSITE LAMINATES REINFORCED WITH CARBON NANOTUBE INTERLAYER USING ELECTROSPRAY DEPOSITION METHOD

by

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LIST OF ABBREVIATIONS

1D	One-dimensional
3D	Three-dimensional
APS	Aminopropyltriethoxysilane
CF	Carbon fiber
CNF	Carbon nanofiber
CNT	Carbon nanotube
CVD	Chemical vapour deposition
DMF	N,N-Dimethylformamide
DSC	Differential scanning calorimetry
EDX	Energy dispersive X-ray
EPD	Electrophoretic deposition
ESD	Electrospray deposition
FESEM	Field emission scanning electron microscope
FTIR	Fourier transform infrared spectroscopy
HRTEM	High resolution transmission electron microscope
IFSS	Interfacial shear strength
ILSS	Interlaminar shear strength
KBr	Potassium bromide
MWCNT	Multi-walled carbon nanotube
NMP	N-Methyl-2-Pyrrolidone
PEI	Polyethyleneimine
POSS	Polyhedral oligomeric silsesquioxane
THF	Tetrahydrofuran
VARTM	Vacuum assisted resin transfer molding

XPS	X-ray Photoelectron Spectroscopy
XRD	X-ray diffraction

LIST OF SYMBOLS

%	Percentage
°	Degree
°C	Degree Celsius
Å	Angstrom
Ω	Ohm
σ	stress
ε	Dielectric constant
η	Viscosity
ζ	Zeta potential
λ	Radiation/wavelength
A	Area
A/g	Ampere/gram
cmHg	Centimeter mercury
cPs	Centipoise
D	Debye
eV	Electronvolt
F	Force
F/g	Farad/gram
g	Gram
g/cm^3	Gram/cubic centimeter
g/mol	Gram/mole
GPa	Gigapascal
Hz	Hertz

kV	Kilovolt
L	Length (mm)
MPa	Megapascal
Min	Minute
mm	Millimeter
mV	Millivolt
ml/h	Milliliter/hour
mW/cm^2	Millwatt/square centimeter
$\mu A/cm^2$	Microampere/square centimeter
µm	Micrometer
nm	Nanometer
P	Maximum load
s/cm	Siemens/meter
T	Temperature
V	Volt
v	Speed of particle
V/cm	Volt/centimeter
V/nm	Volt/nanometer
w/w	weight/weight

TENUNAN GENTIAN KARBON EPOKSI KOMPOSIT LAMINAT DIPERKUAT DENGAN NANOTIUB KARBON DI ANTARA LAPISAN MENGGUNAKAN KAEDAH PEMENDAPAN SEMBURAN ELEKTRO

ABSTRAK

Penghibridan tenunan gentian karbon-nanotiub karbon mendapat banyak perhatian dari kalangan penyelidik dalam bidang epoksi komposit laminat. Dalam kajian ini, kaedah pemendapan semburan elektro digunakan untuk mendepositkan nanotiub karbon pada permukaan tenunan gentian karbon. Pemendapan nanotiub karbon pada permukaan tenunan gentian karbon bertujuan untuk meningkatkan kekasaran permukaan tenunan gentian karbon serta hubungan saling pengaruh mekanikal antara tenunan gentian karbon dan matrik epoksi. Untuk kaedah pemendapan semburan elektro, kestabilan nanotiub karbon dalam pelarut adalah sangat penting semasa proses pemendapan semburan elektro dan N-metil-2-pirolidon adalah terbukti sesuai untuk penyebaran nanotiub karbon kerana kestabilan yang tinggi. Kesan voltan dan masa semburan pemendapan semburan elektro pada morfologi tenunan gentian karbon-nanotiub karbon hibrid telah dikaji. Voltan dan masa semburan optimum untuk mendapatkan lapisan nanotiub karbon yang homogen dan rata pada permukaan tenunan gentian karbon adalah 15 kV dan 15 minit, masing-masing. Daripada ujian gentian tunggal, kaedah pemendapan semburan elektro didapati selamat tanpa sebarang kemerosotan ketara pada kekuatan tenunan gentian karbon-nanotiub karbon hibrid. Epoksi komposit laminat dengan tenunan gentian karbon-nanotiub karbon hibrid yang dioptimumkan dan tenunan gentian karbon tanpa didepositkan nanotiub karbon kemudiannya dihasilkan dan dibandingkan dari segi sifat mekanikal, terma dan dielektrik. Penilaian menunjukkan gentian karbon-nanotiub

karbon hibrid epoksi komposit laminat mempunyai sifat mekanikal, terma dan dielektrik yang lebih tinggi daripada tenunan gentian karbon epoksi komposit laminat. Keputusan menunjukkan bahawa gentian karbon-nanotiub karbon hibrid epoksi komposit laminat mampu meningkatkan kekuatan tegangan, modulus tegangan, kekuatan lentur, modulus lentur, kekuatan ricih antara laminar, konduktiviti terma dan pemalar dielektrik masing-masing sebanyak 21 %, 37 %, 19 %, 27 %, 35 % and 22 %, berbanding tenunan gentian karbon epoksi komposit laminat.

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ABSTRACT

The hybridization of woven carbon fiber-carbon nanotube (CF-CNT) received enormous attention from research communities in the field of epoxy laminates composites. In this study, electrospray deposition (ESD) method was used to deposit carbon nanotube (CNT) on the woven carbon fiber (CF) surface. The deposition of the CNT on the woven CF surface is intended to improve the surface roughness of the woven CF as well as to provide a mechanical interlocking between the woven CF and the epoxy matrix. For ESD method, the stability of the CNT in the solvent is very crucial during the ESD process and N-Methyl-2-Pyrrolidone is proven suitable for dispersing CNT due to high stability. The effect of voltage and spray time of ESD on the morphologies of the woven hybrid CF-CNT has been studied. The optimum voltage and spray time to achieve homogeneous and even CNT coating on the woven CF surface is 15 kV and 15 min, respectively. From single fiber test, the ESD method is found to be safe without any significant degradation on the tensile strength of the woven CF-CNT. The epoxy composite laminates with optimized woven hybrid CF-CNT and woven CF without deposited CNT were then prepared and compared in terms of mechanical, thermal and dielectric properties. The evaluation showed that woven hybrid CF-CNT epoxy composite laminates have greater mechanical, thermal and dielectric properties than woven CF epoxy composite laminates. The results demonstrate that the woven hybrid CF-CNT epoxy composite laminates are capable of improving tensile strength, tensile modulus, flexural strength, flexural modulus,

interlaminar shear strength, thermal conductivity and dielectric constant about 21 %, 37 %, 19 %, 27 %, 25%, 35 % and 22 %, respectively, compared to the woven CF epoxy composite laminates.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Research

CF reinforced epoxy composites exhibit high strength and modulus to weight ratio and broadly used in the aerospace, automobile industries, military and sporting goods. Even though the CF epoxy composite laminates have been widely used in many applications, their potential is still governed by few factors. As is well known, the CF epoxy composite laminates in the form of laminates have poor strength in the direction of through thickness, as no fibers are oriented in the direction of thickness to support transverse load. Thus, CF epoxy composite laminates are vulnerable for the crack to initiate and propagate along the interface. The delamination is one of the frequent failure modes in the laminates composites, which may cause critical reduction in transverse direction strength and stiffness and can lead to catastrophic failure for the whole structure. During manufacturing or service life, the delamination may be introduced by external loading such as tension, static bending, impact loading, cyclic fatigue and compression.

In order for CF epoxy composite laminates to offer better design for advanced components, significant enhancement in the aforementioned properties are necessary. The incorporation of nanofiller, such as carbon nanotubes (CNT) into the matrix of composites has been developed as an efficient method for improving the mechanical and multifunctional properties of CF epoxy composite laminates. The exceptional mechanical and physical properties of CNT have inspired their utilization as additives to enhance the inadequate properties of CF epoxy composite laminates. CNT is one-dimensional with a cylindrical nanostructure of sp^2 hybridized carbon atoms that are densely packed in a honeycomb crystal lattice. CNT has been reported to possess superior mechanical properties, with Young's modulus of 0.27 - 0.95 TPa and tensile strengths of 11 – 63 GPa (Trojanowicz, 2006). CNT is also expected to offer remarkable performances in areas such as thermal and electrical properties. Thermal and electrical conductivity of CNT is up to 3,000W/mK and 1800 S/cm, respectively (Kausar et al., 2016).

There are two common ways for incorporating CNT into the CF epoxy composite laminates. First, CNT is used as reinforcing fillers in the epoxy matrix of the CF epoxy composite laminates to improve their mechanical properties (Davis et al., 2010; Kim et al., 2011). The challenge of this approach is that the uniform dispersion of CNT in the epoxy matrix is difficult to achieve, especially at high concentrations, due to the dramatically increased viscosity of the resin. Highly viscous resin with agglomerated CNT is very difficult to process and always leads to poor performance of CF epoxy composite laminates. In addition, the direct incorporation of the CNT into the epoxy matrix is less effective in improving the interfacial bonding between the CF and epoxy matrix.

Another way is to grow or deposit CNT directly onto CF surface to form a hierarchical reinforcement. Several methods were successfully developed hierarchical hybrid carbon fiber-carbon nanotube (CF-CNT) such as chemical vapour deposition (CVD), electrophoretic deposition (EPD), chemical functionalization and electrospray deposition (ESD) (Susi et al., 2008; Li et al., 2013; Deng et al., 2015; Li et al., 2016). The main motivation for producing hybrid CF-CNT is to improve the interface properties and minimize the existing limitations associated with the matrix dominated properties. For example, CNT could offer interlaminar reinforcement, thus improving resistance to delamination and through thickness properties, without sacrificing the performance of longitudinal direction. In addition, the hybridization of CF with CNT