

**SYNTHESIS AND CHARACTERIZATION OF
PAN NANOFIBER REINFORCED WITH
FUNCTIONALIZED MIXTURE CNT/CNF BY
ELECTROSPINNING TECHNIQUE**

BRYAN BIN GINDANA

**PERPUSTAKAAN
UNIVERSITI MALAYSIA SABAH**

**THESIS SUBMITTED IN PARTIAL
FULFILLMENT FOR THE DEGREE OF MASTER
IN SCIENCE**

**FACULTY OF SCIENCES AND NATURAL
RESOURCES UNIVERSITI MALAYSIA SABAH
2016**



UMS
UNIVERSITI MALAYSIA SABAH

UNIVERSITI MALAYSIA SABAH

BORANG PENGESAHAN STATUS THESIS

JUDUL: **SYNTHESIS AND CHARACTERIZATION OF PAN NANOFIBER REINFORCED WITH FUNCTIONALIZED CNT/CNF BY ELECTROSPINNING TECHNIQUE**

IJAZAH: **IJAZAH SARJANA SAINS
(KIMIA INDUSTRI)**

Saya **BRYAN BIN GINDANA**, Sesi Pengajian **2013-2016**, mengaku membenarkan tesis Ijazah Sarjana Sains ini disimpan di Perpustakaan Universiti Malaysia Sabah dengan syarat-syarat kegunaan seperti berikut:-

1. Tesis ini adalah hak milik Universiti Malaysia Sabah.
2. Perpustakaan Universiti Malaysia Sabah dibenarkan membuat salinan untuk tujuan pengajaran sahaja.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajaran tinggi.
4. Sila tandakan (/)

SULIT

(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia seperti yang termaktub di dalam AKTA RAHSIA 1972)

TERHAD

(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)

/

TIDAK TERHAD

Disahkan oleh,

NURULAIN BINTI ISMAIL

LIBRARIAN

UNIVERSITI MALAYSIA SABAH

(Tandatangan Pustakawan)


BRYAN BIN GINDANA
MS1211017T

Tarikh: 22 Ogos 2016


(Dr. Jahimin A. Asik)
Penyelia



UMS
UNIVERSITI MALAYSIA SABAH

CERTIFICATION

NAME : **BRYAN BIN GINDANA**

MATRIC NO. : **MS1211017T**

TITLE : **SYNTHESIS AND CHARACTERIZATION
OF PAN NANOFIBER REINFORCED
WITH FUNCTIONALIZED CNT/CNF BY
ELECTROSPINNING TECHNIQUE**

DEGREE : **MASTER OF SCIENCE
(KIMIA INDUSTRI)**

VIVA DATE : **15 JUNE 2016**

CERTIFIED BY;

1. SUPERVISOR

Dr. Jahimin A. Asik

Signature



DR. JAHIMIN ASIK @ ABD. RASHID
Pemangku Timbalan Dekan (HEP & ALUMNI)
Fakulti Sains dan Sumber Alam
UNIVERSITI MALAYSIA SABAH

2. CO – SUPERVISOR

Rubia Bte Idris



DECLARATION

I hereby declare that the material in this thesis is my own except for quotations, extractions, equations, summaries and references, which have been duly acknowledged.

14 Dec 2015



.....

Bryan Bin Gindana

MS1211017T



ACKNOWLEDGEMENT

Shalom, thanks be to god the almighty Lord that by His grace, I have been able to complete my research and thesis. Never to forget my beloved family, especially to both of my parents for their supports and endless love regardless of anything, and to my only sister Carolina for inspiring me all the way long. I would also like to take this opportunity to express my sincere gratitude to my supervisors Dr. Jahimin Asik and Miss Rubia Idris; for providing and giving me the chance to undertake my research under their supervision. I have gained so many new experiences beyond my expectations. A million thanks for the valuable guidance and opportunities given. I also sincerely thank my mentor Mr. Puvaneswaren, for his everlasting guidance, sincerity and encouragement in helping me to carry out this project to the last bit of it. I also wish to express my highest regard to all the staff members of FSSA Chemistry laboratory, who had rendered their helps during the period of my research; especially to Mr. Sani, Taipin, Recyheidy, Jerry, and Puan Azimah. Not only that, I also wish to convey my appreciation toward Mrs. Marlenny and Imelda of IPB UMS, Mr Azli of FSSA Forestry, and Mr. Nizam of FST UKM. My uttermost gratitude for my dearest besties; Esteranza Victor Jr, Siti Shakenna Chu, and Billance Fung for their unparalleled endearment to keep uplifting me whenever I felt vulnerable, thank you that you guys has always believe in me that I can pull this through. Not to forget, my laboratory colleagues; Florinna, Arvyvie, and Brian for their helps in every way possible toward the completion of my research. Last but not least, I wish to avail myself of this opportunity, to express a sense of gratitude and love to all my acquaintances that had contributed their comments, criticisms and constructive advices, supports, assistances and the willingness to share priceless information and for everything mentioned and unmentioned. May this study imprint of many people.

Bryan Bin Gindana

14 December 2015

ABSTRACT

In this study, functionalization of CNT and CNF was done using oxidative acid treatment with concentrated HCl and HNO₃ solution mixture at 3:1 ratio. Various process variables such as duration, mode of treatment, agitation and temperature are controlled, and consequently the functional groups growth on the surfaces of both CNT and CNF was determined extensively by the aid of Fourier Transform Infrared Spectroscopy (FTIR). The study proceeds by synthesizing the PAN/CNT-CNF polymer nanocomposite fiber using electrospinning technique. The study used PAN polymer solution containing 10 wt % mixture of CNT: CNF at various ratios of 8:2, 2:8, 6:4, and 4:6. Some critical criterions of operational parameters such as applied voltage (12 kV, 12.5 kV, 13 kV) and working distance (13 cm, 14 cm, 15 cm) were also being optimized beforehand. The available evidences supported that, the optimal operational parameter set was found to be at 15 cm, 13 kV set division as validated by series of scrutinized characterization assessments; where the set up successfully produced the thinnest average nanofiber diameter at 318 nm with the range of 288 to 340 nm. The graphitized nanocomposite fiber was then assessed and characterized comprehensively based on its morphological and elementary study using FESEM-EDX, thermal stability behaviour using TGA and DSC, crystallography assessment by XRD analysis, and conductivity study via EIS. Based on the overall assessment of various field of characterizations, overwhelming evidences has led to the confirmatory conclusion, corroborating PB15Z as the best electrospun PAN/CNT-CNF nanocomposite fiber with an exceptionally thin fiber diameter of 280 nm with 232 nm to 304 nm in range. It possessing the highest carbon content approximately 80 % in total and a good conductivity value recorded at 2.3555×10^{-4} S/m. The fiber also showed the most stable behaviour under intense heat exposure, withstanding the thermal introduction with gradual decrease of weight without any sudden and major fluctuation of weight.

ABSTRAK

SINTESIS DAN PENCIRIAN SERAT NANO PAN DIPERKASA DENGAN CNT/CNF YANG TERFUNGSIONALISASI MENGGUNAKAN KAEADAH PEMINTALAN ELEKTRO

Di dalam kajian ini, kaedah rawatan secara pengoksidaan menggunakan asid dilakukan dengan larutan pekat HCl dan HNO₃ pada nisbah 3:1. Pelbagai pembolehubah seperti masa, mod rawatan, agitasi dan suhu adalah terkawal di dalam kajian ini, dan kemudianya kehadiran kumpulan berfungsi diatas permukaan kedua-dua bahan karbon nano dicirikan dengan bantuan spektroskopi penjelmaan Fourier infra-merah (FTIR). Langkah berikutnya diteruskan dengan menghasilkan serat polimer komposit nano berdasarkan PAN/CNT-CNF menggunakan kaedah pemintalan elektro. Kajian ini menggunakan larutan polimer PAN yang mengandungi 10 % berat campuran CNT: CNF dalam pelbagai nisbah, iaitu 8:2, 2:8, 6:4, dan 4:6. Parameter operasi kritikal seperti voltan gunaan (12 kV, 12.5 kV, 13 kV) dan jarak kerja (13 sm, 14 sm, 15 sm) dioptimumkan terlebih dahulu. Hasil kajian menunjukkan bahawa set parameter operasi optimum adalah 15 sm dan 13 kV; dimana ia berjaya menghasilkan purata diameter serat nano terkecil pada 318 nm dengan julat 288 nm hingga 340 nm. Serat komposit nano yang digrafikkan kemudiannya dicirikan secara menyeluruh dari aspek analisis morfologi dan kajian elemen menggunakan FESEM-EDX, kestabilan terma menggunakan TGA dan DSC, penilaian kristalografi menerusi analisis XRD, dan keupayaan kekonduksian elektrik melalui EIS. Secara keseluruhannya, berdasarkan variasi penilaian dan pencirian, bukti-bukti substansial telah membawa kepada kesimpulan bahawa PB15Z merupakan serat polimer komposit nano yang terbaik, dimana ia mempunyai diameter serat yang kecil iaitu 280 nm dengan julat pada 232 nm hingga 304 nm. Ia turut mempunyai kadar kandungan karbon yang tertinggi pada 80 % kandungan karbon, serta kekonduksian yang baik pada 2.3555×10^4 S/m. Ia juga turut menunjukkan sifat tahan haba kerana tidak menunjukkan kehilangan berat secara drastik pada suhu tinggi.

TABLE OF CONTENTS

	Page
TITLE	i
CERTIFICATION	ii
DECLARATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
ABSTRAK	vi
LIST OF CONTENTS	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiv
LIST OF ABBREVIATIONS	xx
LIST OF SYMBOLS	xxii
LIST OF UNITS	xxiii
CHAPTER 1: INTRODUCTION	1
1.1 Background of Study	1
1.2 Relevance of Study	5
1.3 Objectives of Study	6
1.4 Scope of Study	6
CHAPTER 2: LITERATURE REVIEW	8
2.1 An Introduction to Nanotechnology	8
2.1.1 Nanomaterials	8
2.1.2 Nanocomposite	9
2.2 Carbon and Carbon Nanomaterials	10
2.2.1 The Allotropes of Carbon	11
2.2.2 Carbon Nanotubes	13
a. Physiochemical properties of Carbon Nanotubes	17
2.2.3 Carbon Nanofiber	21
a. Physiochemical Properties of Carbon Nanofiber	23

2.3	Functionalized Carbon Nanomaterials	27
2.3.1	Functionalization Approaches	27
2.3.2	Advantages of Functionalized Carbon Nanomaterials	29
2.3.3	Application of Functionalized Carbon Nanomaterials	31
2.4	Polymer and Polymer Nanofibers	32
2.4.1	Polymer Classification	33
2.4.2	Polyacrylonitrile Polymer (PAN)	35
2.4.3	PAN nanofiber	35
2.5	Nanofiber Treatment	36
2.5.1	PAN Nanofiber Treatment	37
a.	Stabilization	37
b.	Carbonization	38
c.	Graphitization	39
2.6	Nanocomposite Preparation	40
2.7	Electrospinning Technology in Composite Preparation	41
2.7.1	Type of Electrospinning Setup	42
2.7.2	Operational Principle	43
2.7.3	Effect of Parameter	44
a.	Solution Parameters	45
b.	Processing Parameters	47
2.8	Instrumentations	52
2.8.1	Functional Group Determination	52
2.8.2	Crystallography Study	52
2.8.3	Thermal Analysis	53
a.	Thermogravimetric Analysis (TGA)	53
b.	Differential Scanning Calorimetry (DSC)	54
2.8.4	Morphology and Elementary Study	55
a.	Field Emission Scanning Microscopy with Dispersive X-ray Analysis (FE-SEM/EDX)	55
b.	Transmission Electron Microscopy (TEM)	56
2.8.5	Conductivity Analysis	56

CHAPTER 3: METHODOLOGY	58
3.1 Overview of the Study	58
3.2 Research Material and Experimental Design	58
3.3 Functionalization of Carbon Nanomaterials	61
3.4 Preparation of Polyacrylonitrile Carbon Nanomaterials Polymer Solution Mixture	62
3.4.1 Preparation of Polyacrylonitrile Solution Mixture	63
3.4.2 Preparation of PAN/CNT-CNF Solution Mixture	63
3.5 Electrospinning Set up and Parameters	64
3.5.1 Electrospinning Workstation Set up	64
3.6 Electrospinning of Nanocomposite Fiber	66
3.6.1 Electrospinning Process	66
3.6.2 Electrospinning Operational Parameters	66
3.6.3 Optimization of Electrospinning Operational Parameter	67
3.6.4 Synthesis of Electrospun Polyacrylonitrile Carbon Nanotube/ Carbon Nanofiber (PAN/CNT-CNF) Nanocomposite Fiber	68
3.7 Electrospun Nanocomposite Fiber Heat Treatment	69
3.7.1 Stabilization	70
3.7.2 Carbonization	70
3.7.3 Graphitization	70
3.8 Characterization	72
3.8.1 Viscosity Analysis	73
3.8.2 Morphological and Surface Analysis	73
a. Field Emission Scanning Electron Microscopy with Energy Dispersive X-ray Analysis	74
b. Transmission Electron Microscopy	75
3.8.3 Thermal Stability Analysis	75
a. Thermogravimetric Analysis	76
b. Differential Scanning Calorimetry	76
3.8.4 Functional Groups Analysis	77

3.8.5 Crystallography Analysis	78
3.8.6 Conductivity Analysis	78
CHAPTER 4: RESULTS AND DISCUSSION	80
4.1 Assessment of Functionalized Carbon Nanomaterials	80
4.1.1 Functional Groups Study	80
4.1.2 Crystallography Study	83
4.1.3 Thermal Stability Study	85
4.1.4 Texture Morphology Study	90
4.2 Assessment of Polymer/Carbon Nanomaterials Slurry	95
4.2.1 Viscosity Test	97
4.3 Assessment of Optimisation Electrospinning Parameters	99
4.3.1 Morphological Study of Optimisation Electrospun Fiber (5:5) PAN/CNT-CNF Nanocomposite Fibers	102
4.3.2 Thermal Stability of Optimisation Electrospun Fiber (5:5) PAN/CNT-CNF Nanocomposite Fibers	115
4.3.3 Summary of Optimisation Electrospinning Parameters	125
4.4 Assessment of Various Ratio Divisions of Electrospun PAN/CNT-CNF Nanocomposite Fiber Produced Via Optimised Electrospinning Parameters	126
4.4.1 Morphological Study of PAN/CNT-CNF Nanocomposite Fiber	127
4.4.2 Morphological Comparison of PB15Z, PC15Z, PD15Z, and PE15Z Nanocomposite Fiber	141
4.4.3 Thermal Stability of PAN/CNT-CNF Nanocomposite Fiber	144
4.4.4 Elementary Study of PAN/CNT-CNF Nanocomposite Fiber	152
4.4.5 Crystallography Study of Optimised PAN/CNT-CNF Nanocomposite Fiber	154
4.4.6 Conductivity Study of PAN/CNT-CNF Nanocomposite Fiber	156
4.4.7 Functional Group Study of Selected PAN/CNT-CNF Nanocomposite Fiber	159

CHAPTER 5: CONCLUSIONS	162
5.1 Summary	162
5.2 Study Limitations	167
5.3 Future Study	167
REFERENCES	169

LIST OF TABLES

	Page
Table 2.1: The typical physical properties comparison of CNT and other materials	19
Table 2.2: Typical properties comparison of VGCNF, SWNT, MWNT, and carbon fiber (CF)	26
Table 3.1: The specifications of carbon nanomaterials	59
Table 3.2: Combination ratios of CNT and CNF to PAN solution mixture	62
Table 3.3: Testing parameter specifications of Sample A	66
Table 3.4: Synthesis parameters of PAN/CNT-CNF composite nanofiber	67
Table 4.1: Viscosity values of polymer composite slurry at room temperature	95
Table 4.2: Summarized fiber texture morphology study	111
Table 4.3: TGA-DTG thermograms summarized data of electrospun fiber	117
Table 4.4: Summary of DSC thermograms and elementary analysis	122
Table 4.5: Optimum operational parameters obtained from optimisation	123
Table 4.6: PAN/CNT-CNF nanocomposite fibers samples	124
Table 4.7: Summarized Morphology Study of Electrospun Fiber PAN/CNT-CNF	138
Table 4.8: TGA-DTG thermograms summarized data of electrospun fiber	145
Table 4.9: DSC thermograms summarized data of electrospun fiber	150

Table 4.10:	Elemental mass percentage of optimised PAN PAN/CNT-CNF Nanocomposite Fiber	152
Table 4.11:	XRD Diffractograms Peak of Electrospun PAN/CNT-CNF Nanocomposite Fibers	154
Table 4.12:	Conductivity values of PAN/CNT-CNF Nanocomposite Pellet	155
Table 4.13:	Summarize FTIR spectra of graphitized PAN and PB15Z fiber	158

LIST OF FIGURES

	Page
Figure 2.1: Allotropes of carbon (a) diamond, (b) graphite, (c) carbon nanotube, (d) graphene, and (e) fullerene	12
Figure 2.2: Conceptual diagram of (a) single walled carbon nanotube (SWNT) and (b) multi walled carbon nanotube (MWNT)	14
Figure 2.3: The graphene honeycomb network with the graphite vector lattice	16
Figure 2.4: Schematic representation of relation between carbon nanotube and graphene making up different chiralities (a) armchair, (b) zigzag, and (c) chiral nanotube	17
Figure 2.5: High-resolution transmission electron microscopy (HRTEM) image of sidewall VGCNF with cup stacked structure model	23
Figure 2.6: Polymer and their classifications	34
Figure 2.7: Stabilization reaction of PAN fiber	38
Figure 2.8: Carbonization reaction of PAN fiber	39
Figure 2.9: The overall heat treatment of PAN fibers	40
Figure 2.10: Classifications of fibers by diameter	42
Figure 2.11: Type of electrospinning set up (a) horizontal type and (b) vertical type	43
Figure 2.12: General set up of electrospinning technique	44
Figure 2.13: Jet path between tip of capillary and collector	49
Figure 2.14: Flow of solution pathway through the capillary tip	51

Figure 3.1:	Flow chart of overall experimental design	60
Figure 3.2:	Raw carbon nanomaterials	61
Figure 3.3:	Polyacrylonitrile polymer powder	63
Figure 3.4:	Schematic diagram of electrospinning set up	65
Figure 3.5:	Schematic diagram of quartz tube sets specifications	71
Figure 3.6:	Schematic diagram of tubular muffle furnace heating system set up	72
Figure 3.7:	Brookfield Viscometer	73
Figure 3.8:	Field Emission Scanning Electron Microscope Energy Dispersive X-ray	74
Figure 3.9:	FEI Technai Spirit Transmission Electron Microscope	75
Figure 3.10:	PerkinElmer Thermogravimetric Analyzer	76
Figure 3.11:	PerkinElmer Differential Scanning Calorimeter	77
Figure 3.12:	PerkinElmer Fourier Transform Infrared Spectroscopy	78
Figure 3.13:	Solartron Analyzer Electrochemical Impedance Spectroscopy	79
Figure 4.1:	FTIR spectra of (a) pristine CNF, (b) pristine CNT, (c) functionalized CNF, and (d) functionalized CNT	81
Figure 4.2:	FTIR spectra of (A) high region, and (B) low region of samples (a) pristine CNF, (b) pristine CNT, (c) functionalized CNF, and (d) functionalized CNT	82
Figure 4.3:	XRD pattern of (a) pristine CNT, (b) pristine CNF, (c) functionalized CNT, and (d) functionalized CNF	84



- Figure 4.4: TGA-DTG thermograms of (a) raw MWCNT and (b) functionalized MWCNT 86
- Figure 4.5: TGA-DTG thermograms of (a) raw CNF and (b) functionalized CNF 88
- Figure 4.6: SEM images with 9KX magnification of (a) raw CNT (b) functionalized CNT, (c) raw CNF, and (d) functionalized CNF 91
- Figure 4.7: TEM images of functionalized MWCNT viewed from (a) 9K mag, (b) 18.5K mag, and (c) 49K mag 93
- Figure 4.8: TEM images of functionalized CNF viewed from (a) 4.8K mag, (b) 13K mag, and (c) 30K mag 95
- Figure 4.9: The viscosity of various polymer slurry based on the nanocomposite composition ratio at room temperature 98
- Figure 4.10: The visual observation of the (a) electrospinning set up, and (b) ongoing electrospinning process 100
- Figure 4.11: Structure of electrospun of PAN/CNT-CNF nanofiber composite (a) before heat treatment, (b) after heat treatment 101
- Figure 4.12: FESEM images of P A13X at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 102
- Figure 4.13: FESEM images of P A13Y at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 104
- Figure 4.14: FESEM images of P A13Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 105
- Figure 4.15: FESEM images of P A14X at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 106
- Figure 4.16: FESEM images of P A14Y at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 108

- Figure 4.17: FESEM images of P A14Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 109
- Figure 4.18: FESEM images of P A15X at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 110
- Figure 4.19: FESEM images of P A15Y at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 111
- Figure 4.20: FESEM images of P A15Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 112
- Figure 4.21: TGA-DTG thermograms of (a) PA15X, (b) PA15Y, (c) PA15Z, and (d) PAN fiber 117
- Figure 4.22: TGA thermograms of combined (a) P A15X, (b) P A15Y, (c) P A15Z, and (d) graphitized PAN fiber 118
- Figure 4.23: DSC thermograms of (a) P A15X, (b) P A15Y, (c) P A15Z, and (d) graphitized PAN fiber 122
- Figure 4.24: FESEM images of P B15Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 128
- Figure 4.25: TEM images of P B15Z viewed from (a) 890 X mag, (b) 2.9K X mag, (c) 6.8K X mag, and (d) 23K X mag 129
- Figure 4.26: FESEM images of P C15Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 131
- Figure 4.27: TEM images of P C15Z viewed from (a) 890 X mag, (b) 2.9K X mag, (c) 6.8K X mag, and (d) 18.5K X mag 132
- Figure 4.28: FESEM images of P D15Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 134
- Figure 4.29: TEM images of P D15Z viewed from (a) 890 X mag, (b) 2.9K X mag, (c) 6.8K X mag, and (d) 23K X mag 135

- Figure 4.30: FESEM images of P E15Z at (a) low magnification 5K X, (b) medium magnification 10K X, and (c) high magnification 25K X 137
- Figure 4.31: TEM images of P E15Z viewed from (a) 890 X mag, (b) 2.9K X mag, (c) 6.8K X mag, and (d) 13K X mag 139
- Figure 4.32: Fiber Diameter Comparison between Various Sample Ratios 142
- Figure 4.33: TGA-DTG thermograms of (a) PB15Z, (b) PC15Z, (c) PD15Z, and (d) PE15Z 146
- Figure 4.34: Summarized Remaining Ash Value of Electrospun PAN/CNT-CNF Nanocomposite Fiber 149
- Figure 4.35: DSC thermograms of (a) PE15Z, (b) PC15Z, (c) PB15Z, and (d) PD15Z 151
- Figure 4.36: EDX spectrum of PB15Z optimised PAN/CNT-CNF nanocomposite fiber 153
- Figure 4.37: The XRD diffractograms of (a) PD15Z, (b) PC15Z, (c) PB15Z, and (d) PE15Z 155
- Figure 4.38: The example of impedance plot from PE15Z 157
- Figure 4.39: The FTIR spectra of (a) graphitized PAN fiber produced in 15 cm, 13 kV, and (b) PB15Z fiber 160

LIST OF ABBREVIATIONS

1D	-	One dimension
2D	-	Two dimension
3D	-	Three dimension
AC	-	Alternating current
C ₆₀	-	Fullerene
CF	-	Carbon fiber
CNF	-	Carbon nanofiber
CNT	-	Carbon nanotube
ConA	-	Concanavalin
DMAC	-	Dimethylacetamide
DMF	-	Dimethylformamide
DMSO	-	Dimethylsulfoxide
DNA	-	Deoxyribonucleic acid
DSC	-	Differential scanning calorimetry
DTG	-	Differential thermogravimetric
EDX	-	Energy dispersive x-ray
EIS	-	Electrochemical impedance spectroscopy
FESEM	-	Field emission scanning electron microscopy
FTIR	-	Fourier transform infrared spectroscopy
MWNT	-	Multiwall carbon nanotube
NMR	-	Nuclear magnetic resonance
PAN	-	Polyacrylonitrile
PEEK	-	Polyether ether ketone
PMMA	-	Polymethyl methacrylate
PP	-	Polypropylene
PS	-	Polystyrene
Pt	-	Platinum
SEM	-	Scanning electron microscope
SWNT	-	Single wall carbon nanotube
TEM	-	Transmission electron microscopy
Tg	-	Glass transition temperature

TG	-	Thermogravimetry
TGA	-	Thermogravimetric analysis
Tm	-	Melting temperature
VGCNT-	-	Vapour grown carbon nanotube
XRD	-	X-ray diffraction

LIST OF SYMBOLS

°	-	Degree
E	-	Voltage
I	-	Current
Z'	-	Real impedance
Z''	-	Imaginary impedance
θ	-	Theta
π	-	Pi
σ	-	Conductivity
Ω	-	Ohm

LIST OF UNITS

cm	-	Centimeter
cm ⁻¹	-	Reciprocal wavelength
cm ³	-	Centimeter cubic
cP	-	Centipoise
Ea	-	Activation energy
eV	-	Electron volt
g	-	Gram
g/cm ³	-	Density
GPa	-	Gigapascal
hr	-	Hour
K	-	Kilo
KV	-	Kilovolt
m	-	Meter
mA	-	Milliampere
mg	-	Milligram
min	-	Minute
ml	-	Milliliter
mm	-	Millimeter
mW	-	Milliwatts
nm	-	Nanometer
S/m	-	Electrical conductivity
TPa	-	Terapascal
V	-	Volt
W/mK ⁻¹	-	Thermal conductivity
wt	-	Weight
µm	-	Micrometer
Ω.cm	-	Electrical resistivity

REFERENCES

- Abuilaiwi, F.A., Laoui, T., Al-harthi, M., & Atieh, M.A. 2010. Modification and Functionalization of Multiwalled Carbon Nanotube (MWCNT) via Fischer Esterification. *The Arabian Journal for Science and Engineering.* **35**(1):37–48.
- Al-Saleh, M.H., & Sundararaj, U. 2009. A Review of Vapor Grown Carbon Nanofiber/Polymer Conductive Composites. *Carbon.* **47**(1):2–22.
- Al-Saleh, M. H., & Sundararaj, U. 2011. Review of The Mechanical Properties of Carbon Nanofiber/Polymer Composites. *Composites Part A: Applied Science and Manufacturing.* **42**(12):2126–2142.
- Alves, A.K., Bergmann, C.P., & Berutti, F.A. 2013. *Novel Synthesis and Characterization of Nanostructured Materials.* London: Springer.
- Amiri, A., Zardini, H.Z., Shanbedi, M., Maghrebi, M., Baniadam, M., & Tolueinia, B. 2012. Efficient Method for Functionalization of Carbon Nanotubes by Lysine and Improved Antimicrobial Activity and Water-Dispersion. *Materials Letters.* **72**(2012):153–156.
- Andrews, R., & Weisenberger, M.C. 2004. Carbon Nanotube Polymer Composites. *Current Opinion in Solid State and Materials Science.* **8**(1):31–37.
- Ardanuy, M., Rodríguez-Perez, M.A., & Algaba, I. 2011. Electrical Conductivity and Mechanical Properties of Vapor-Grown Carbon Nanofibers/Trifunctional Epoxy Composites Prepared by Direct Mixing. *Composites Part B: Engineering.* **42**(4):675–681.
- Asari, N., Tessonniere, J.-P., Rinaldi, A., Reiche, S., & Kutty, M.G. 2012. Chemically Modified Multi-walled Carbon Nanotubes (MWCNTs) with Anchored Acidic Groups. *Sains Malaysiana.* **41**(5):603–609.

- Azizian, J., Entezari, M., Zomorodbakhsh, S., & Shamel, A. 2012. Synthesis of Water-Soluble Single-Walled Nanotubes by Functionalization via Esterification. *Global Journal of Science Frontier Research Chemistry*. **12**(3):12–16.
- Balasubramanian, K., & Burghard, M. 2005. Chemically Functionalized Carbon Nanotubes. *Small*. **1**(2):180–92.
- Baykal, A., Senel, M., Unal, B., Karaoglu, E., Sozeri, H., & Toprak, M. S. 2013. Acid Functionalized Multiwall Carbon Nanotube/Magnetite (MWCNT)-COOH/Fe₃O₄ Hybrid: Synthesis, Characterization and Conductivity Evaluation. *Journal of Inorganic and Organometallic Polymers and Materials*. **23**(3):726–735.
- Bourourou, M., Holzinger, M., Bossard, F., Hugenell, F., Maaref, A., & Cosnier, S. 2015. Chemically Reduced Electrospun Polyacrylonitrile–Carbon Nanotube Nanofibers Hydrogels as Electrode Material for Bioelectrochemical Applications. *Carbon*. **87**(2015):233–238.
- Brockman, S. 2012. Basics of Electrochemical Impedance Spectroscopy. Application Note. Warminster: Gamry Instruments.
- Chae, H. G., Liu, J., & Kumar, S. 2006. *Carbon Nanotube-Enabled Materials*. In M. J. O'Connell (eds.). *Carbon Nanotube: Properties and Applications*, pp. 213–276. USA: Taylor & Francis Group.
- Chakrabarti, K. 2010. Controlled Lowering of Graphitization Temperature of Electrospun Poly(Acrylonitrile) Based Carbon Fiber by Carbon Nanotube Embedment. *Materials Letters*. **64**(14):1607–1610.
- Chellaram, C., Murugaboopathi, G., John, A.A., Sivakumar, R., Ganesan, S., Krithika, S., & Priya, G. 2014. Significance of Nanotechnology in Food Industry. *APCBEE Procedia*, **8**(2014):109–113.

- Chien, A.T., Newcomb, B.A., Sabo, D., Robbins, J., Zhang, Z.J., & Kumar, S. 2014. High-strength Superparamagnetic Composite Fibers. *Polymer*. **55**(16):4116–4124.
- Cho, C. W., Cho, D., Ko, Y.G., Kwon, O.H., & Kang, I.K. 2007. Stabilization, Carbonization, and Characterization of PAN Precursor Webs Processed by Electrospinning Technique. *Carbon Letters*. **8**(4):313–320.
- Darányi, M., Csesznok, T., Sarusi, I., Kukovecz, Á., Kónya, Z., Erdőhelyi, A., & Kiricsi, I. 2010. Beneficial Effect Of Multi-Wall Carbon Nanotubes on the Graphitization of Polyacrylonitrile (PAN) Coating. *Processing and Application of Ceramics*. **4**(2):59–62.
- Ding, D., Wei, H., Wang, Y., Guo, J., Zhang, X., Yan, X., Jiang, D., Qiu, B. 2014. Nano-Chemical Engineering and Nano-Processes in Manufacturing Multi-Functional Nanocomposites. *Chemical and Process Engineering*. **1**(202):1–3.
- Edelson, E. 1992. Carbon Allotropes: And Then There Were Three. *Mosaic*. **23**(3):1-11.
- Endo, M., Kim, Y. a., Hayashi, T., Nishimura, K., Matusita, T., Miyashita, K., & Dresselhaus, M.S. 2001. Vapor-grown Carbon Fibers (VGCFs)-Basic Properties and Their Battery Applications. *Carbon*. **39**(2011):1287–1297.
- Enyashin, A.N., & Ivanovskii, A. L. 2014. Structural and Electronic Properties Of New 1D and 2D Carbon Allotropes with Mixed Sp₁–Sp₃ Hybridization Types. *Chemical Physics Letters*. **609**(2014):15–20.
- Fisher, J.E. 2006. Carbon Nanotubes: Structure and Properties. In Y. Gogotsi (eds.). *Carbon Nanotubes*, pp. 41–76. USA: Taylor & Francis Group.
- Gao, D., Qiao, H., Wang, Q., Cai, Y., & Wei, Q. 2011. Structure , Morphology and Thermal Stability of Porous Carbon Nanofibers Loaded with Cobalt Nanoparticles. *Journal of Engineered Fibers and Fabrics*. **6**(4):6–9.

- Gindana, B., Jamil, A.A., Brandon, B., Jr, B., Tan, F., Ali, S.A.M., Asik, J.A., & Idris, R. 2015. Chemical Surface Modification of CNTs via Three Oxidative Acid Treatments. *Advanced Materials Research*. **1107**(2015):320-325.
- Giron, D. 2002. Applications of Thermal Analysis and Coupled Techniques in Pharmaceutical Industry. *J. Therm. Anal. Cal.* **68**(2002):335–357.
- Gomes, H.T., Samant, P.V., Serp, P., Kalck, P., Figueiredo, J.L., & Faria, J.L. 2004. Carbon Nanotubes and Xerogels as Supports of Well-Dispersed Pt Catalysts for Environmental Applications. *Applied Catalysis B: Environmental*. **54**(3):175–182.
- Gu, S., Wu, Q., & Ren, J. 2008. Preparation And Surface Structures Of Carbon Nanofibers Produced From Electrospun PAN Precursors. *New Carbon Materials*. **23**(2):171–176.
- Han, J. 2004. Structure and Properties of Carbon Nanotubes. In M. Meyyappan (eds.). *Carbon Nanotubes: Science and Applications*, pp. 2–21. USA: CRC Press.
- Harris, P.J.F. 2009. *Carbon Nanotube Science: Synthesis, Properties and Applications*. New York: Cambridge.
- Hemalatha, M. 2012. Studies on Synthesis, Structure and Optical Properties of Nickel Nanoparticles. *Journal Of Ovonic Research*. **8**(2):47–51.
- Hennrich, F., Chan, C., Moore, V., Rolandi, M., & O'Connell, M. 2006. Carbon Nanotubes: Properties and Applications. In M. J. O'Connell (eds.). *The Element Carbon*, pp. 1–18. USA: Taylor & Francis Group.
- Hou, H., & Reneker, D.H. 2004. Carbon Nanotubes on Carbon Nanofibers: A Novel Structure Based on Electrospun Polymer Nanofibers. *Advanced Materials*. **16**(1):69–73.

- Hou, P.X., Liu, C., & Cheng, H.M. 2008. Purification of Carbon Nanotubes. *Carbon*. **46**(15), 2003–2025.
- Hsiao, K., Alms, J., & Advani, S.G. 2003. Use of Epoxy/Multiwalled Carbon Nanotubes as Adhesives to Join Graphite Fibre Reinforced Polymer Composites. *Nanotechnology*. **791**(14):791–793.
- Hsieh, Y.C., Chou, Y.C., Lin, C.P., Hsieh, T.F., & Shu, C.M. 2010. Thermal Analysis of Multi-walled Carbon Nanotubes by Kissinger's Corrected Kinetic Equation. *Aerosol and Air Quality Research*. **10**:212–218.
- Huang, Z., Zhang, Y., Kotaki, M., & Ramakrishna, S. 2003. A Review on Polymer Nanofibers by Electrospinning and Their Applications in Nanocomposites. *Composites and Science Technology*. **63**(2003):2223–2253.
- Hussain, S., Jha, P., Chouksey, A., Raman, R., Islam, S. S., Islam, T., Choudhary, P.K., & Harsh. 2011. Spectroscopic Investigation of Modified Single Wall Carbon Nanotube (SWCNT). *Journal of Modern Physics*. **2**(6):538–543.
- Hussein, A.K. 2015. Applications of Nanotechnology in Renewable Energies—A Comprehensive Overview and Understanding. *Renewable and Sustainable Energy Reviews*. **42**(2015):460–476.
- Idris, R., Puvaneswaren, K., Abdullah, N., & Asik, J. 2014. Investigation On Morphology , Conductivity And Thermal Stability Study Of The Electrospun PAN. *International Journal of Science Environment*. **3**(4):1402–1411.
- Jaybhaye, S., & Sharon, M. 2010. Hydrogen Storage by Carbon Nanomaterial. In M. Sharon & M. Sharon (eds.). *Carbon Nanoform and Applications*, pp. 248-278. USA: McGraw Hill.

Jing, M., Wang, C., Wang, Q., Bai, Y., & Zhu, B. 2007. Chemical Structure Evolution and Mechanism During Pre-Carbonization of PAN-Based Stabilized Fiber in the Temperature Range of 350–600°C. *Polymer Degradation and Stability*. **92**(9):1737–1742.

Ju, Y.W., Choi, G.R., Jung, H.R., & Lee, W.J. 2008. Electrochemical Properties of Electrospun PAN/MWCNT Carbon Nanofibers Electrodes Coated with Polypyrrole. *Electrochimica Acta*. **53**(19):5796–5803.

Jr, C. E. C. 2013. *Introduction to Polymer Chemistry*. (3rd edition). United States: CRC Press.

Karacan, I. 2012. *Thermal Stabilization of Polyacrylonitrile Fibers*. Turkey: Society of Plastics Engineers.

Kim, B., Bui, N., Yang, K., Cruz, M. E., & Ferraris, J. P. 2009. Electrochemical Properties of Activated Polyacrylonitrile/pitch Carbon Fibers Produced Using Electrospinning. *Bulletin of the Korean Chemical Society*. **30**(9):1967-1972.

Kim, C., & Yang, K.S. 2003. Electrochemical Properties of Carbon Nanofiber Web as an Electrode for Supercapacitor Prepared by Electro-spinning. *Applied Physics Letters*, **83**(6):1216–1218.

Kim, P., Shi, L., Majumdar, A., & McEuen, P.L. 2001. Thermal Transport Measurements of Individual Multiwalled Nanotubes. *Physical Review Letters*. **87**(21):1-4.

Klumpp, C., Kostarelos, K., Prato, M., & Bianco, A. 2006. Functionalized Carbon Nanotubes as Emerging Nanovectors for the Delivery of Therapeutics. *Biochimica et Biophysica Acta*, **1758**(3):404–412.

Khenoussi, N., Drean, E., Schacher, L., Adolphe, D. C., & Balard, H. 2016. Preparation and Morphology Study of Carbon Nanotube Reinforced Polyacrylonitrile Preparation and Morphology Study of Carbon Nanotube

- Ko, T.H., Liao, Y.K., & Liu, C.H. 2007. Effects of Graphitization of PAN-Based Carbon Fiber Cloth on Its Use as Gas Diffusion Layers in Proton Exchange Membrane Fuel Cells. *New Carbon Materials*. **22**(2):97–101.
- Kumar, D., & Sharon, M. 2010. Characterization of Carbon Nanomaterials by Scanning Electron Microscopy. In M. Sharon & M. Sharon (eds.). *Carbon Nanoform and Applications*, pp. 531. USA: McGraw Hill.
- Kumar, M. 2010. Chemical Vapor Deposition and Synthesis of Carbon Nanomaterials. In M. Sharon & M. Sharon (eds.). *Carbon Nanoform and Applications*, pp. 28–39. USA: McGraw Hill.
- Kumar, P. 2012. *Effect of Collector on Electrospinning to Fabricate Aligned Nanofiber Effect of Collector on Electrospinning to Fabricate Aligned Nanofiber*. Department of Biotechnology & Medical Engineering. Rourkela: National Institute of Technology.
- Kundu, S. (2009). *Surface Modifications of Carbon Nanotubes and Their Application in Electro-Catalysis*. Department of Chemistry Laboratory. Germany: Ruhr-University Bochum.
- Lawrence, J. G., Berhan, L. M., & Nadarajah, A. 2008. Elastic Properties and Morphology of Individual Carbon Nanofibers. *American Chemical Society*. **2**(6):11–14.
- Lee, S. 2012. Structural Evolution of Polyacrylonitrile Fibers in Stabilization and Carbonization. *Advances in Chemical Engineering and Science*. **2**(2):275–282.
- Li, X., Wong, S. Y., Tjiu, W. C., Lyons, B. P., Oh, S. A., & He, C. Bin. 2008. Non-Covalent Functionalization of Multi Walled Carbon Nanotubes and Their Application for Conductive Composites. *Carbon*. **46**(5):829–831.

- Li, Z., & Wang, C. 2013. *One-Dimensional Nanostructures Electrospinning Technique and Unique Nanofibers*. New York: Springer.
- Lin, J. F., Kamavaram, V., & Kannan, A. M. 2010. Synthesis and Characterization of Carbon Nanotubes Supported Platinum Nanocatalyst for Proton Exchange Membrane Fuel Cells. *Journal of Power Sources*. **195**(2):466–470.
- Liu, W., Cheng, L., Zhang, H., Zhang, Y., Wang, H., & Yu, M. 2007. Rheological Behaviors of Polyacrylonitrile/ 1-Butyl-3- Methylimidazolium Chloride Concentrated Solutions. *International Journal of Molecular Sciences*. **2007**(8):180–188.
- Lozano, K. 2000. Vapor-Grown Carbon-Fiber Composites: Processing and Electrostatic Dissipative Applications. *JOM-J Miner Met Mater Soc*. **52**(11):34–36.
- Maitra, T., Sharma, S., Srivastava, A., Cho, Y. K., Madou, M., & Sharma, A. 2012. Improved Graphitization and Electrical Conductivity of Suspended Carbon Nanofibers Derived From Carbon Nanotube/Polyacrylonitrile Composites by Directed Electrospinning. *Carbon*. **50**(5):1753–1761.
- Marques, R. R. N., Machado, B. F., Faria, J. L., & Silva, a. M. T. 2010. Controlled Generation of Oxygen Functionalities on the Surface of Single-Walled Carbon Nanotubes by HNO_3 Hydrothermal Oxidation. *Carbon*. **48**(5):1515–1523.
- Marulanda, J.M. (ed). 2011. *Carbon Nanotube Industrial Applications*. Rijeka: InTech.
- Marulanda, J.M. (ed). 2011. *Functionalization Methods of Carbon Nanotubes and its Applications*. Rijeka: InTech.
- Marshall, M. W., Popa-Nita, S., & Shapter, J. G. 2006. Measurement of Functionalised Carbon Nanotube Carboxylic Acid Groups Using a Simple Chemical Process. *Carbon*. **44**(7):1137–1141.

- Mital, J., Bahi, O. P., & Mathur, R. B. (1997). Single Step Carbonization and Graphitization of Highly Stabilized PAN Fibers. *Carbon*. **35**(8):1196–1197.
- Mohammadian, M., & Haghi, A. K. 2012. Biopolymer Electrospun Nanofibers. *Materiale Plastice*. **49**(4), 301–311.
- Mottaghitalab, V., & Haghi, A. K. 2011. A study on Electrospinning of Polyacrylonitrile Nanofibers. *Korean J. Chem. Eng.* **28**(1):114–118.
- Nataraj, S.K., Yang, K.S., & Aminabhavi, T.M. 2012. Polyacrylonitrile-based Nanofiber-A State of the Art Review. *Progress in Polymer Science*. **37**(3):487–513.
- Oh, T., Lee, K., Kim, K. S., & Choi, C. K. 2004. Comparison of the Nano-Structure due to C = O and C = C Double Bond. *Journal of the Korean Physical Society*. **45**(3):705–708.
- Oliveira, J. L. de, Campos, E. V. R., Bakshi, M., Abhilash, P. C., & Fraceto, L. F. 2014. Application of Nanotechnology for the Encapsulation of Botanical Insecticides for Sustainable Agriculture: Prospects and Promises. *Biotechnology Advances*. **32**(8):1550–1561.
- Razavi, R.S. (ed). 2012. *Recent Researches in Corrosion Evaluation and Protection*. Rijeka: InTech.
- Park, H.K., Kim, S. M., Lee, J. S., Park, J.H., Hong, Y.K., Hong, C. H., & Kim, K. K. 2015. Flexible Plane Heater: Graphite and Carbon Nanotube Hybrid Nanocomposite. *Synthetic Metals*. **203**(2015):127–134.
- Lin, T. (ed.). 2011. *Nanofibers - Production, Properties and Functional Applications*. Shanghai: InTech.
- Qi, X., Ruan, X., & Pan, C. 2007. Graphitization of solid Carbon Nanofibers at an Unexpectedly Low Temperature. *Materials Letters*. **61**(21):4272–4275.

Ra, E.J., An, K.H., Kim, K.K., Jeong, S.Y., & Lee, Y.H. 2005. Anisotropic Electrical Conductivity of MWCNT/PAN Nanofiber Paper. *Chemical Physics Letters*. **413**(2015):188–193.

Rahaman, M.S.A., Ismail, A. F., & Mustafa, A. 2007. A Review of Heat Treatment on Polyacrylonitrile Fiber. *Polymer Degradation and Stability*. **92**(8):1421–1432.

Gogotsi, Y. (ed). 2006. *Chemistry of Carbon Nanotubes*. USA: Taylor & Francis Group.

Reilly, R.M. 2007. Carbon Nanotubes: Potential Benefits and Risks of Nanotechnology in Nuclear Medicine. *Journal of Nuclear Medicine: Official Publication, Society of Nuclear Medicine*. **48**(2007):1039–1042.

Rodoplu, D., Mutlu, M., & Ph, D. 2012. Effects of Electrospinning Setup and Process Parameters on Nanofiber Morphology Intended for the Modification of Quartz Crystal Microbalance Surfaces. *Journal of Engineered Fibers and Fabrics*. **7**(2):118-123.

Rokhina, E. V, Lahtinen, M., Makarova, K., Jegatheesan, V., & Virkutyte, J. 2012. Theoretical and Practical Aspects of Chemical Functionalization of Carbon Nanofibers (CNFs): DFT calculations and Adsorption Study. *Bioresource Technology*. **113**(2012):127–131.

Saini, R., Saini, S., & Sharma, S. 2010. Nanotechnology: The Future Medicine. *Journal of Cutaneous and Aesthetic Surgery*. **3**(1):32–33.

Scarselli, M., Castrucci, P., & De Crescenzi, M. 2012. Electronic and Optoelectronic Nano-Devices based on Carbon Nanotubes. *Journal of Physics: Condensed Matter*. **24**(2012):1-36.

Schnitzler, E., & Kobelnik, M. 2002. Characterization of Pharmaceuticals By Thermal Analysis. *Exact and Soil Sciences, Agrarian S. and Engineering*, **8**(1):91–100.

- Sebastián, D., Suelves, I., Moliner, R., & Lázaro, M.J. (2010). The effect of the Functionalization of Carbon Nanofibers on Their Electronic Conductivity. *Carbon*. **48**(15):4421–4431.
- Shanov, V., Yun, Y., & Schulz, M. J. 2006. Synthesis And Characterization Of Carbon Nanotube Materials (Review). *Journal of the University of Chemical Technology and Metallurgy*. **41**(4):377–390.
- Sharma, C. S., Katepalli, H., Sharma, A., & Madou, M. 2011. Fabrication and Electrical Conductivity of Suspended Carbon Nanofiber Arrays. *Carbon*. **49**(5):1727–1732.
- Sharon, M., & Sharon, M. 2010. Carbon Nanoforms and Applications. In M. Sharon & M. Sharon (eds.). *Introduction to the Nanoworld of Carbon*, pp. 1–125. USA: McGraw Hill.
- Silva, G.A. 2004. Introduction to Nanotechnology and its Applications to Medicine. *Surgical Neurology*. **61**(3):216–220.
- Simmons, T. J., Bult, J., Hashim, D. P., Linhardt, R. J., & Ajayan, P. M. 2009. Noncovalent Functionalization as an Alternative to Oxidative Acid Treatment of Single Wall Carbon Nanotubes with Applications for Polymer Composites. *ACS Nano*, **3**(4):1–7.
- Singh, P., Andola, H.C., Rawat, M.S.M., Pant, G.J.N., & Purohit, V.K. 2011. Fourier Transform Infrared (FT-IR) Spectroscopy in An-Overview. *Research Journal of Medicinal Plant*. **5**(2):127–135.
- Singh, R.P., Zhang, M., & Chan, D. 2002. Toughening of a Brittle Thermosetting Polymer: Effects of Reinforcement. *Journal of Material Science*. **37**(4):781–788.
- Song, Z., Hou, X., Zhang, L., & Wu, S. 2011. Enhancing Crystallinity and Orientation by Hot-Stretching to Improve the Mechanical Properties of

Electrospun Partially Aligned Polyacrylonitrile (PAN) Nanocomposites. *Materials*. **4**(12):621–632.

Soni, H.R., & Jha, P.K. 2014. Vibrational and Elastic Properties of 2D Carbon Allotropes: A First Principles Study. *Solid State Communications*. **189**(2014):156-62.

Stuart, B. 2004. *Infrared Spectroscopy: Fundamentals and Applications*. England: John Wiley & Sons.

Suh, W.H., Suslick, K.S., Stucky, G.D., & Suh, Y.H. 2009. Nanotechnology, Nanotoxicology, and Neuroscience. *Progress in Neurobiology*. **87**(41):133–170.

Tadano, S., & Giri, B. 2012. X-ray Diffraction as a Promising Tool to Characterize Bone Nanocomposites. *Science and Technology of Advanced Materials*. **12**(2011):1-11

Tenne, R., Remskar, M., Enyashin, A., & Seifert, G. 2008. Inorganic Nanotubes and Fullerene-Like Structures (IF). In A. Jorio & G. Dresselhaus (eds.). *Carbon nanotubes: Advanced topics in the synthesis, structure, properties and applications*, (pp. 631-669). New York: Springer.

Thostenson, E., Li, C., & Chou, T. 2005. Nanocomposites in Context. *Composites Science and Technology*. **65**(2005):491–516.

Thostenson, E.T., Ren, Z., & Chou, T.W. 2001. Advances in the Science and Technology of Carbon Nanotubes and Their Composites: A Review. *Composites Science and Technology*. **61**(13):1899–1912.

Tibbetts, G.G., Lake, M.L., Strong, K.L., & Rice, B.P. 2007. A Review of The Fabrication and Properties of Vapor-Grown Carbon Nanofiber/Polymer Composites. *Composites Science and Technology*. **67**(2007):1709–1718.

- Varela-Rizo, H., Bittolo-Bon, S., Rodriguez-Pastor, I., Valentini, L., & Martin-Gullon, I. 2012. Processing and Functionalization Effect in CNF/PMMA Nanocomposites. *Composites Part A: Applied Science and Manufacturing*. **43**(4):711–721.
- Velasco-Santos, C., Martinez-Hernandez, A.L., Fisher, F., Ruoff, R., & Castano, V. M. 2003. Dynamical-mechanical and Thermal Analysis of Carbon Nanotube-Methyl-Ethyl Methacrylate Nanocomposites. *Journal of Physics D: Applied Physics*. **36**(12):1423–1428.
- Venkateswarlu, M., Reddy, K. N., Rambabu, B., & Satyanarayana, N. 2000. A.C Conductivity And Dielectric Studies Of Silver-Based Fast Ion Conducting Glass System. *Solid State Ionics*. **127**(2000):177–184.
- Vrieze, S. De, Camp, T. Van, Nelvig, A., Hagstrom, B., Westbroek, P., & Clerck, K. De. 2009. The Effect of Temperature And Humidity on Electrospinning. *J. Mater. Sci.* **44**(2009):1357–1362.
- Wang, S. 2009. Optimum Degree of Functionalization for Carbon Nanotubes. *Current Applied Physics*, **9**(5):1146–1150.
- Wangxi, Z., Jie, L., & Gang, W. 2003. Evolution of Structure and Properties of PAN Precursors During Their Conversion to Carbon Fibers. *Carbon*. **41**(2003):2805–2812.
- Wu, M., Wang, Q., Li, K., Wu, Y., & Liu, H. 2012. Optimization of Stabilization Conditions for Electrospun Polyacrylonitrile Nanofibers. *Polymer Degradation and Stability*. **97**(8):1511–1519.
- Xue, Y., Bao, L., Xiao, X., Ding, L., Lei, J., & Ju, H. 2011. Noncovalent Functionalization of Carbon Nanotubes with Lectin for Label-Free Dynamic Monitoring of Cell-Surface Glycan Expression. *Analytical Biochemistry*. **410**(2011): 92–97.

- Yamamoto, T., Watanabe, K., & Hernandez, E.R. 2008. Mechanical Properties, Thermal Stability and Heat Transport in Carbon Nanotubes. In A. Jorio, G. Dresselhaus, & M. S. Dresselhaus (eds.). *Carbon Nanotubes Advanced Topics in the Synthesis, Structure, Properties and Applications*, pp. 165-194. New York: Springer.
- Yan, C., Chen, Z., Peng, Y., Guo, L., & Lu, Y. 2012. Stable Lithium-Ion Cathodes from Nanocomposites of VO₂ Nanowires and CNTs. *Nanotechnology*. **23**(47): 1-7.
- Yellampalli, S. (ed). 2011. *Functionalization of Carbon Nanotubes Polymer Nanocomposites*. Rijeka: InTech
- Yellampalli, S. (ed). 2001. *Polymer/Carbon Nanotube Nanocomposites*. Rijeka: InTech.
- Young, R. J., & Lovell, P. A. (2011). *Introduction to Polymers* (3rd ed.). USA: Taylor & Francis Group.
- Yudianti, R., Onggo, H., Saito, Y., Iwata, T., & Azuma, J. 2011. Analysis of Functional Group Sited on Multi-Wall Carbon Nanotube Surface. *The Open Materials Science*. **5**(2011):242–247.
- Zaikov, G.E. (ed). 2011. *Electrospinning of Nanofibers from Introduction to Application*. New York: Nova Science Publishers.
- Zhang, H., Xu, L., Yang, F., & Geng, L. 2010. The Synthesis of Polyacrylonitrile/Carbon Nanotube Microspheres by Aqueous Deposition Polymerization under Ultrasonication. *Carbon*. **48**(3):688–695.
- Zhang, J., Zou, H., Qing, Q., Yang, Y., Li, Q., Liu, Z., Gou, X., & Du, Z. 2003. Effect of Chemical Oxidation on the Structure of Single-Walled Carbon Nanotubes. *The Journal of Physical Chemistry B*. **107**(16):3712–3718.

- Zhang, Q., Zhang, S., & Zhang, L. 2014. Microwave-Assisted Modification of Carbon Nanotubes with Biocompatible Polylactic Acid. *Journal of Materials Science and Chemical Engineering*. **2**(2014):7–12.
- Zhao, Y., Yang, X., Tian, J., Wang, F., & Zhan, L. 2010. A Facile and Novel Approach Toward Synthetic Polypyrrole Oligomers Functionalization of Multi-Walled Carbon Nanotubes as PtRu Catalyst Support For Methanol Electro-Oxidation. *Journal of Power Sources*. **195**(15):4634–4640.
- Zhou, F.L., Gong, R.H., & Porat, I. 2009. Three-Jet Electrospinning Using A Flat Spinneret. *J. Mater. Sci.* **44**(2009):5501–5508.
- Zhou, H., Wang, T., & Duan, Y. Y. 2013. A Simple Method for Amino-Functionalization of Carbon Nanotubes And Electrodeposition to Modify Neural Microelectrodes. *Journal of Electroanalytical Chemistry*. **688**(2013):69–75.