

Contents

CERTIFICATE	<i>ii</i>
DECLARATION BY THE CANDIDATE.....	<i>iii</i>
CERTIFICATE FROM THE SUPERVISOR	<i>iii</i>
COPYRIGHT TRANSFER CERTIFICATE	<i>iv</i>
ABSTRACT	<i>v</i>
DEDICATION.....	<i>viii</i>
ACKNOWLEDGEMENTS	<i>ix</i>
Contents	<i>x</i>
<i>List of Figures</i>	<i>xvii</i>
<i>List of Tables</i>	<i>xxii</i>
<i>List of Abbreviations</i>	<i>xxiii</i>
<i>List of Nomenclature.....</i>	<i>xxv</i>
<i>Preface</i>	<i>xxviii</i>
<i>Chapter 1. Introduction</i>	<i>1</i>
1.1. Background.....	1
1.1.1. FRP Composites	2
1.1.2. Nanocomposite	3
1.2. Motivation	8
<i>Chapter 2. Literature Review</i>	<i>13</i>
2.1. Introduction	13

2.2.	Epoxy.....	13
2.3.	Nanoparticles Reinforcement	17
2.3.1.	Metal-based nanoparticles	18
2.3.2.	Clay nanoparticles.....	18
2.3.3.	Ceramic nanoparticles.....	19
2.3.4.	Polymer-based nanoparticles	19
2.3.5.	Carbon-based nanoparticles	20
2.4.	Graphene.....	20
2.5.	CNT	22
2.6.	Fabrication of GNP and CNT epoxy nanocomposite.....	26
2.7.	Research Gap.....	27
2.8.	Research Aims and Objectives	30
2.9.	Structure of The Thesis.....	31

Chapter 3. Development of Nanocomposite by Magnetic Field Induced Alignment of GNP
35

3.1.	Introduction	35
3.2.	Method: Physical phenomena of applied DC electromagnetic-coerced alignment of Fe ₃ O ₄ -GNP	35
3.2.1.	Rotation of Fe ₃ O ₄ -GNP particles	39
3.2.2.	Chaining of Fe ₃ O ₄ -GNP nanoparticles.....	42
3.2.3.	Migration of Fe ₃ O ₄ -GNP nanoparticles	47
3.2.4.	Slackening of aligned Fe ₃ O ₄ -GNP nanoparticles.....	48
3.3.	Experimental section	49
3.4.	Results and discussion.....	50

3.4.1.	Experimental results	50
3.5.	Model Results	52
3.5.1.	Rotation.....	53
3.5.2.	Chaining of nanoparticles	55
3.5.3.	Migration	57
3.5.4.	Slackening.....	58
3.5.5.	Considerations on the model results	58
3.6.	Conclusion	60

Chapter 4. Experimental Characterization Optimising Alignment Parameters of GNP Epoxy Base nanocomposite..... 62

4.1.	Introduction	62
4.2.	Experimental section	62
4.2.1.	Basic materials.....	63
4.2.2.	Synthesis of Fe ₃ O ₄ and Fe ₃ O ₄ -GNP	63
4.2.3.	Preparation of GNP epoxy and Fe ₃ O ₄ -GNP epoxy nanocomposites	64
4.3.	Characterization, morphology and microstructure of GNP, Fe ₃ O ₄ -GNP and nanocomposites	68
4.3.1.	HR-XRD (High Resolution X-Ray Diffraction).....	68
4.3.2.	FTIR (Fourier transform infrared spectroscopy).....	68
4.3.3.	Raman measurements	68
4.3.4.	TGA (Thermogravimetric analysis).....	69
4.3.5.	DSC (Differential scanning calorimetry).....	69
4.3.6.	AFM (Atomic force microscopy)	69
4.3.7.	XPS (X-ray photoelectron spectroscopy analysis).....	69
4.3.8.	BET (Brunauer–Emmett–Teller) analysis.....	70
4.3.9.	Exploration of the alignment of the Fe ₃ O ₄ -GNP.....	70
4.3.10.	HR-SEM and HR-TEM analysis	70

4.3.11.	Chemorheological behaviours of epoxy during curing	70
4.3.12.	Measurement of magnetic properties.....	71
4.4.	Results and discussion	71
4.4.1.	HR-XRD analysis	71
4.4.2.	FTIR (Fourier transform infrared spectroscopy).....	74
4.4.3.	Raman spectroscopy	74
4.4.4.	TGA (Thermogravimetric analysis).....	75
4.4.5.	DSC (Differential scanning calorimetry).....	77
4.4.6.	XPS (X-ray photoelectron spectroscopy analysis).....	79
4.4.7.	BET (Brunauer–Emmett–Teller) analysis.....	81
4.4.8.	Exploration of the alignment of the Fe ₃ O ₄ -GNP.....	82
4.4.9.	SEM and TEM analysis	82
4.4.10.	AFM analysis.....	86
4.4.11.	Magnetic properties of GNP, Fe ₃ O ₄ , and Fe ₃ O ₄ -GNP	90
4.4.12.	Chemorheological behaviour of epoxy during curing.....	91
4.5.	Conclusion	92

Chapter 5. *Fracture and Failure Analysis of GNP and Aligned Fe₃O₄-GNP Epoxy*

Nanocomposite	94	
5.1.	Introduction	94
5.2.	Experimental.....	95
5.2.1.	Basic Materials	95
5.2.2.	Preparation of GNP epoxy and aligned Fe ₃ O ₄ -GNP epoxy nanocomposites.....	95
5.3.	Mechanical properties.....	95
5.3.1.	Tensile tests	95
5.3.2.	Compression tests	96
5.3.3.	Compact tension (CT) test for fracture toughness	96
5.3.4.	CTOD _c measurement by clip gauges	99

5.3.5.	Fracture surface analysis.....	100
5.4.	Results	102
5.4.1.	Tensile Properties	102
5.4.1.1.	Maximum tensile load	104
5.4.1.2.	Maximum tensile extension.....	105
5.4.1.3.	Young's modulus	106
5.4.1.4.	Yield strength	107
5.4.1.5.	Toughness.....	108
5.4.2.	Compression Properties	109
5.4.2.1.	Compressive yield strength	110
5.4.2.2.	Compressive modulus	112
5.4.3.	Fracture toughness and fracture energy	114
5.4.3.1.	Maximum CT load	115
5.4.3.2.	Stress intensity factor	116
5.4.3.3.	Strain energy release rate.....	118
5.4.3.4.	Critical Crack Tip opening displacement	119
5.4.4.	Fracture surface analysis.....	122
5.4.4.1.	Stereo zoom optical microscopy.....	122
5.4.4.2.	Atomic force microscopy	123
5.5.	Discussion.....	130
5.6.	Conclusions	135

Chapter 6. Fatigue Analysis of GNP and Aligned Fe₃O₄-GNP Epoxy Nanocomposite. 136

6.1.	Introduction	136
6.2.	Experimental procedure.....	137
6.2.1.	Materials and specimen preparation the nanocomposites	137
6.2.2.	Cyclic fatigue and FCGR test	138
6.2.3.	Fatigue fracture surface analysis.....	142

6.3. Result.....	142
6.3.1. Cyclic fatigue loading and its response.....	143
6.3.2. The impact of nanoparticles on thresholds for fatigue crack growth, ΔK_{th} and ΔG_{th}	147
6.3.3. The influence of nanoparticles on the FCGR.....	150
6.3.4. The impact of nanoparticles on the constant of the Paris law	153
6.3.5. Fatigue fracture surface analysis.....	158
6.4. Discussion.....	163
6.4.1. Thermal softening	164
6.4.2. Fatigue crack growth mechanism	165
6.5. Conclusion.....	168
Chapter 7. Fracture Energy of CNT/Epoxy Nanocomposites with Progressive Interphase Debonding, Cavitation, and Plastic Deformation of Nanovoids	170
7.1. Introduction	170
7.2. A theoretical multi-scale modelling approach.....	171
7.2.1. General concepts.....	171
7.2.1.1. Macro-scale:	172
7.2.1.2. Micro-scale:.....	173
7.2.1.3. Nano-scale:.....	173
7.2.2. Mean mechanical properties and stiffness tensor.....	173
7.2.3. Description of RVE	174
7.3. Energy release rate procedure in multi-scale modelling	177
7.4. Elastic debonding induced toughness improvement	183
7.5. Cavitation.....	185
7.6. Plastic deformation of nanovoids	186
7.7. Results and discussion.....	191

7.7.1.	Effect of the interphase properties on cavitation-induced toughness improvement.....	192
7.7.2.	Growth of nanovoid and plastic deformation.....	192
7.7.3.	Experimental comparison of fracture energy, analytical evaluation and error.....	194
7.8.	Conclusions	199
	Supplementary	200
Chapter 8.	<i>Conclusion and Future Scope</i>	202
8.1.	Introduction	202
8.2.	Conclusion	202
8.2.1.	Development of nanocomposite by Magnetic Field Induced Alignment of Graphene Nanoplatelets	
	203	
8.2.2.	Experimental Characterization Optimising Alignment Parameters of GNP epoxy base	
	nanocomposite.....	203
8.2.3.	Fracture and Failure Analysis of GNP and aligned Fe ₃ O ₄ -GNP epoxy Nanocomposite	204
8.2.4.	Fatigue Analysis of GNP and aligned Fe ₃ O ₄ -GNP epoxy Nanocomposite.....	205
8.2.5.	Fracture Energy of CNT/Epoxy Nanocomposites with Progressive Interphase Debonding,	
	Cavitation, and Plastic Deformation of Nanovoids	206
8.3.	Future Scope	208
REFERENCES	210
<i>List of Publications</i>	232