

**STUDIES ON EROSION WEAR PERFORMANCE OF FIBER
REINFORCED VINYL ESTER RESIN BASED COMPOSITES**

by

SANDEEP KUMAR

CENTRE FOR POLYMER SCIENCE AND ENGINEERING

Submitted

In fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER 2013

CERTIFICATE

This is to certify that the thesis entitled “**STUDIES ON EROSION WEAR PERFORMANCE OF FIBER REINFORCED VINYL ESTER RESIN BASED COMPOSITES**” being submitted by **Mr. Sandeep Kumar** to the Centre for Polymer Science and Engineering (CPSE), Indian Institute of Technology (IIT) Delhi, India, is worthy of consideration for the award of the degree of **Doctor of Philosophy** in Polymer Science and Engineering and is an authentic record of original bonafide research work carried out by him under my supervision and guidance and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard.

The ideas, experimental work, results, analyses and conclusions reported in this thesis are original and have not been previously, to the best of my knowledge, submitted, in part or full, to any other University or Institute for the award of any degree or diploma.

Dr. Bhabani Kumar Satapathy

Associate Professor

Centre for Polymer Science and Engineering
Indian Institute of Technology Delhi

ACKNOWLEDGEMENTS

The completion of a PhD thesis is strenuous mission, taking one to the limit and back again. The terrible nature of this mission entails the assistance of a number of people to help bring it to a conclusion. Completion of this dissertation was made possible by an IIT Delhi doctoral fellowship awarded to the author and funded by the Ministry of Human Research and Development (MHRD), India.

Special sincere thanks are given to my adviser **Dr. Bhabani Kumar Satapathy** for his expert advice, considerable time and effort directed towards ensuring the completion of this PhD project in particular and throughout my tenure as his student. Your advice and assistance has been unwavering. No one is more helpful and supportive than you.

Comments, discussions, advice, and especially for the facility for erosion testing from **Dr. Amar Patnaik** are invaluable and much appreciated. Thank you for your direction and guidance in many matters, particularly in helping me stay the course to complete my PhD, and giving your time to review this dissertation. Thanks to both of you for sacrificing your Fridays and weekends for valuable suggestions in writing of research papers and thesis.

I would like to give thanks to my research committee members: **Prof. B. L. Deopura** (Chairman), **Prof. Naresh Bhatnagar** (External Expert), and **Prof Anup Kumar Ghosh** (Internal Expert) for their helpful and valuable discussions about the results after every presentation of PhD progress report. I also appreciate the encouragement from faculty members of the Centre for Polymer Science and Engineering I.I.T. Delhi: **Prof. Saurindra N. Maiti, Prof. Veena Choudhary and Dr. Josemon Jacob**. For other contributions to the successful completion of this dissertation, I also acknowledge the following colleagues and friends: **Mr. Tez Singh, Mr. Sunil Kumar, Dr. Naresh Dayma, Mr. Dibyendu Das, Mr. Rakesh Kumar Kachhap, Mr. Harjeet Singh Jaggi, Mr. Ritesh Kundal, Mr. Mukesh Kumar** and technical

staff members-**Mr. Surender Sharma, Mr. Shivkant and Mr. Kapoor**. To all others who have assisted me, no matter how small a contribution, I give you my thanks.

My deepest acknowledgments are given to my family. Many thanks to my parents, parents-in-law, sister, brothers and wife: without their support I could not have completed this work. When times were the most difficult, they were there to keep me on track.

Finally, but most importantly, I thank God for giving me the will power and strength to complete this thesis.

Date:

Place: New Delhi

(Sandeep Kumar)

Abstract

Chopped-fiber reinforced vinyl ester resin composites with glass fiber, carbon fiber, aramid fiber and their combinations as reinforcements have been fabricated and investigated for their erosive wear performance vis-à-vis their thermal and mechanical response in the range of 20-50 wt.-%. The descriptions of the experimental methods used for the successful fabrication and characterization of the short-fiber reinforced composites and hybrid composites have been presented. The physical (density and void fraction), mechanical (tensile, flexural, impact and hardness), thermal (TGA) and thermo-mechanical (DMA) characteristics of composites have been critically investigated. The principles of micromechanics have been applied to the experimental mechanical data in order to semi qualitatively analyze the validity of the various composite theories such as Rule of mixture, Halpin-Tsai, Christensen model etc. A series of erosion experiments were conducted using an air jet type test rig according to ASTM G76 on these composites under multi parametric test conditions. For this purpose, an experimental schedule has been adopted following L_{16} design of experiments approach using Taguchi's orthogonal arrays. The method enables reduction in the number of experiments without sacrificing the information to be extracted. A set of five variables have been selected namely: impingement angle, impact velocity, fiber loading, stand-off distance and erodent size. For the L_{16} design of experiment, each factor has been considered at four levels. The analysis has successfully led to the optimization of multi parametric experimental variables for the minimization of erosion rate. Furthermore, the steady state erosion rate performance has been investigated as a function of erodent size, impact velocity and impingement angle. An optimum weight fraction of short fibers in these composites has been observed to improve their erosion wear resistance of the investigated composites where the extent of improvement depended on the type of fibers in short-fiber reinforced binary composites and fiber-combination based hybrid composites. The steady state erosive wear performance correlations to viscoelastic properties have also been developed. An empirical

predictive model for the estimation of erosive wear rate following *Dimensional Analysis* approach based on Buckingham's Pi Theorem has been developed. It has been demonstrated that this model reflected the effects of various factors on the erosion rate and their predictive results have been consistent with the experimental observations. The experimental results of slurry erosion wear of hybrid composites as a function of impact velocity, impact angle and erodent size as per ASTM G 73-98 have also been presented. The worn surface morphological characterization of the eroded surface has been carried out to understand the possible mechanistic attributes responsible for erosive wear in air (solid particle impingement) and liquid (slurry) mediums. The overall performance ranking of investigated composites has also been carried out by adopting the Technique for Order preference by Similarity to Ideal Solution (TOPSIS) method while resorting to "multiple attribute decision making" (MADM) approach.

Table of Contents

Certificate	i
Acknowledgements	ii
Abstract	iv
List of Figures	xii
List of Tables	xx
Nomenclature	xxiii
CHAPTER-1: INTRODUCTION AND LITERATURE SURVEY	1-55
1.1. Composite materials	2
1.2. Fiber reinforced polymer composites	3
1.3. Wear performance evaluation	5
1.4. Erosion performance (dry air-jet) of polymers and fiber-reinforced binary polymer composites	7
1.5. Erosion (dry air-jet) performance of hybrid composites	16
1.6. Correlation of air-jet erosion performance to material properties	18
1.7. Erosion (slurry-jet) performance of composites	19
1.8. Optimization of erosive wear performance	21
1.9. Predictive modelling of erosion performance by empirical / semi-empirical approaches	23
1.10. Erosion performance of short / chopped fiber-reinforced polymer-matrix composites: State-of-the art	26
1.11. Challenges and scope in erosive wear performance	35
1.12. Motivation for the research work	36
1.13. Justification on selection of raw materials	39

1.14. Objectives	42
CHAPTER-2: EXPERIMENTAL: FABRICATION AND CHARACTERIZATION OF COMPOSITESS	56-76
2.1. Raw materials for composites fabrication	57
2.2. Preparation of composites	57
2.3. Characterization of composites	60
2.3.1. Physical and mechanical characterization	60
2.3.1.1. Density and void fraction	60
2.3.3.2. Tensile testing	61
2.3.3.3. Flexural Testing	62
2.3.4.4. Impact testing	62
2.3.4.5. Micro-hardness test	63
2.3.4.6. Dynamic mechanical properties	63
2.3.2. Thermal characterization	64
2.3.2.1. Thermogravimetric analysis (TGA)	64
2.3.2.2. Matrix Burn-off test	64
2.3.3. Erosion (dry air-jet) performance assessment	65
2.3.4. Slurry-jet erosion: Test equipment and erosion characteristics	69
2.3.5. Scanning electron microscopy (SEM)	72
2.4. Distribution and adhesion of fiber within the composites	72
2.5. Characterization of sand erodent particles	73
2.5.1. Density of erodent	73
2.5.2. Scanning electron microscopy (SEM) of erodent	75
CHAPTER-3: EVALUATION OF FIBER REINFORCED COMPOSITES: MECHANICAL AND SOLID PARTICLE EROSION	77-144

3.1. Materials	78
3.2. Physical and mechanical properties	78
3.2.1. Void content	78
3.2.2. Tensile properties	81
3.2.3. Prediction of tensile modulus	83
3.2.4. Flexural properties	87
3.2.5. Impact strength	88
3.2.6. Vickers microhardness	89
3.3. Thermo-mechanical properties of composites	90
3.3.1. Viscoelastic storage modulus	90
3.3.2. Viscoelastic loss modulus	93
3.3.3. Damping factor	95
3.3.4. Cole-Cole plot	97
3.4. Thermal stability by thermogravimetric analysis (TGA)	98
3.5. Matrix-burn off method	102
3.6. Erosive wear performance of the composites	102
3.6.1. Taguchi analysis and response optimization	102
3.6.2. ANOVA and the effects of factors	108
3.6.3. Confirmation experiment	111
3.7. Steady state erosion rate	113
3.7.1. Influence of impingement angle	113
3.7.2. Influence of impact velocity	117
3.7.3. Influence of erodent size	120
3.8. Thermo-mechanical correlations to erosion performance	123
3.9. Worn surface morphology of the composites	127

3.10. Chapter summary	137
CHAPTER-4: EVALUATION OF CHOPPED FIBER REINFORCED COMPOSITES: MECHANICAL AND SOLID PARTICLE EROSION BEHAVIORS	145-189
4.1. Materials	146
4.2. Physical and mechanical properties	146
4.2.1. Void content	146
4.2.2. Tensile properties	147
4.2.3. Prediction of tensile modulus	149
4.2.4. Flexural properties	149
4.2.5. Impact strength	150
4.2.6. Microhardness	150
4.3. Thermo-mechanical properties	150
4.3.1. Effect of fiber weight fraction on storage modulus (E')	151
4.3.2. Effect of fiber weight fraction on loss modulus (E'')	153
4.3.3. Effect of fiber weight fraction on mechanical damping factor ($\tan \delta$)	154
4.3.4. Cole-Cole plots	157
4.4. Thermal Stability by thermogravimetric analysis (TGA)	157
4.5. Matrix-burn off method	158
4.6. Erosive wear performance of the composites	159
4.6.1. Taguchi analysis and response optimization	159
4.6.2. ANOVA and the effects of factors	162
4.6.3. Confirmation experiment	163
4.7. Steady state erosion behaviour	165
4.7.1. Influence of impingement/collision angle	165
4.7.2. Variation of impact velocity	167

4.7.3. Variation of erodent size	168
4.8. Thermo-mechanical correlations to erosion performance	170
4.9. Wear surface morphology of eroded hybrid composite surface	171
4.10. Chapter summary	184
CHAPTER-5: SLURRY EROSION PERFORMANCE OF CHOPPED FIBER REINFORCED HYBRID COMPOSITES	190-209
5.1. Materials	191
5.2. Slurry erosion	191
5.3. Effect of operating variables on slurry erosion rate	192
5.3.1. Effect of impingement angle	192
5.3.2 Effect of velocity	194
5.2.3 Effect of erodent particle size	195
5.3 Morphology of slurry exposed surface	197
5.4 Chapter summary	206
Chapter-6: WEAR FORECASTING AND PERFORMANCE RANKING	210-245
6.1. Wear forecasting from semi-empirical information	211
6.1.1. Model formulation	211
6.1.2. Buckingham's pi theorem	212
6.1.3. Dimensionless products	214
6.1.4. Model assessment	218
6.1.5. Model verification / validation	218
6.1.5.1. Theoretical and experimental erosion rate as a function of impingement angles	220
6.1.5.2. Theoretical and experimental erosion rate as a function of impact velocity	223

6.1.5.3. Theoretical and experimental erosion rate as a function of erodent size	226
6.1.6. Correlation between the theoretical and experimental erosion rates	229
6.2. Ranking of the composite	232
6.2.1. TOPSIS method	232
6.2.2. Ranking of the alternatives for air-jet erosion process	234
6.2.3. Ranking of the alternatives for slurry jet erosion process	239
6.4. Chapter summary	243
Chapter-7: CONCLUSION	246-251
7.1. Conclusive summary	247
7.2. Scope for future work	251
List of Publications	252
Brief bio-data of the Author	253