



Wear of Advanced Materials

**Edited by
J. Paulo Davim**

ISTE

 **WILEY**

Wear of Advanced Materials

Wear of Advanced Materials

Edited by
J. Paulo Davim

ISTE

 **WILEY**

First published 2012 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

Apart from any fair dealing for the purposes of research or private study, or criticism or review, as permitted under the Copyright, Designs and Patents Act 1988, this publication may only be reproduced, stored or transmitted, in any form or by any means, with the prior permission in writing of the publishers, or in the case of reprographic reproduction in accordance with the terms and licenses issued by the CLA. Enquiries concerning reproduction outside these terms should be sent to the publishers at the undermentioned address:

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.iste.co.uk

www.wiley.com

© ISTE Ltd 2012

The rights of J. Paulo Davim to be identified as the author of this work have been asserted by him in accordance with the Copyright, Designs and Patents Act 1988.

Library of Congress Cataloging-in-Publication Data

Wear of advanced materials / edited by J. Paulo Davim.

p. cm.

Includes bibliographical references and index.

ISBN 978-1-84821-352-4

1. Mechanical wear. 2. Strength of materials. I. Davim, J. Paulo.

TA418.4.W4174 2012

620.1'1292--dc23

2011044639

British Library Cataloguing-in-Publication Data

A CIP record for this book is available from the British Library

ISBN: 978-1-84821-352-4

Printed and bound in Great Britain by CPI Group (UK) Ltd., Croydon, Surrey CR0 4YY



Table of Contents

Preface	xi
Chapter 1. Carbon Fabric-reinforced Polymer Composites and Parameters Controlling Tribological Performance	1
Jayashree BIJWE and Mohit SHARMA	
1.1. Introduction to polymeric tribo-composites.	3
1.2. Carbon fibers as reinforcement	6
1.2.1. Classification of carbon fibers	7
1.2.2. Classification of fabric weaves	12
1.3. Carbon fabric-reinforced composites	12
1.3.1. Manufacturing methods to create CFRCs	13
1.3.2. Performance evaluation of composites	14
1.3.3. Tribological properties	14
1.4. Tribo-performance of CFRCs: influential parameters	15
1.4.1. Influence of the processing technique	16
1.4.2. Influence of fabric contents	19
1.4.3. Fabric orientation effect	29
1.4.4. Effect of fabric weave on performance properties	30
1.4.5. Influence of strengthening the fiber matrix interface.	33

1.4.6. Influence of the type of polymer used	41
1.4.7. Influence of the molecular weight of a polymer	42
1.5. Concluding remarks	46
1.6. Bibliography.	50
A1.1. Appendix I: Various techniques for developing CFRCs by compression molding	54
A1.1.1. Hand lay-up technique	54
A1.1.2. Impregnation technique	55
A1.1.3. Polymer film technique	55
A1.1.4. Powder prepreg technique	55
A2. Appendix II: Characterization methods for CFRCs	57
A2.1. Physical characterization	57
A2.2. Mechanical properties.	59

**Chapter 2. Adhesive Wear Characteristics
of Natural Fiber-reinforced Composites 61**

Belal F. YOUSIF

2.1. Introduction	62
2.1.1. Why natural fibers?	62
2.1.2. Tribology of polymeric composites based on natural fibers.	63
2.2. Preparation of polyester composites	67
2.2.1. Preparation of FRPC	67
2.2.2. Preparation of palm-oil fibers and PORP composites	69
2.2.3. NaOH treatment	69
2.2.4. Preparation of PORP composites	70
2.3. Specifications of the fibers and composites.	70
2.3.1. Interfacial adhesion of palm-oil fibers	70
2.3.2. Mechanical properties of the composites	74
2.4. Tribo-experimental details.	76
2.4.1. Experimental procedure	78
2.4.2. Examination of worn surfaces	79
2.4.3. Parameters measured	80

2.4.4. Results and discussion	80
2.4.5. Effect of operating parameters.	80
2.4.6. Effect of 6% NaOH treatment	87
2.4.7. Effect of wet and dry contact conditions	89
2.5. Summary	93
2.6. Bibliography	94
Chapter 3. Resistance to Cavitation Erosion:	
Material Selection	99
Jinjun LU, Zhen LI, Xue GONG, Jiesheng HAN and Junhu MENG	
3.1. Cavitation erosion of materials – a brief review	99
3.2. Measuring the wear resistance of a material to cavitation erosion by using a vibratory cavitation erosion apparatus.	101
3.2.1. General view of an ultrasonic vibratory apparatus	101
3.2.2. Determination of the wear resistance of a material to cavitation erosion	103
3.2.3. Experimental details	105
3.3. Material selection	108
3.3.1. Metal and alloys.	109
3.3.2. Advanced ceramic.	112
3.3.3. Polymer.	113
3.3.4. Comparison	114
3.4. Conclusion	115
3.5. Acknowledgement	116
3.6. Bibliography	116
Chapter 4. Cavitation of Biofuel Applied in the Injection Nozzles of Diesel Engines	119
Hengzhou WO, Xianguo HU, Hu WANG and Yufu XU	
4.1. Introduction	120
4.2. General understanding of cavitation erosion . . .	122
4.2.1. Mechanism of cavitation erosion	122

4.2.2. Synergistic effect of cavitation erosion and corrosion	129
4.3. Hydraulic characteristics of cavitation flow	131
4.3.1. Numerical models and validation	133
4.3.2. Effect of boundary pressure on cavitation	133
4.3.3. Effect of nozzle geometry on cavitation	136
4.4. Influence of fuel property on cavitation.	139
4.4.1. Cavitating flow characteristics	140
4.4.2. Variation in the characteristics of dimensionless parameters	142
4.4.3. Effect of fuel properties on cavitation inception	144
4.5. Cavitation erosion of biofuel in the diesel injection nozzle	146
4.5.1. Effect of cavitation erosion on a nozzle	146
4.5.2. Location of cavitation erosion in a nozzle	148
4.5.3. Factors that influence cavitation erosion in nozzles.	151
4.5.4. Effect of biofuel on the erosion of nozzles	154
4.6. Conclusion	155
4.7. Acknowledgments	156
4.8. Bibliography.	157

**Chapter 5. Wear and Corrosion Damage
of Medical-grade Metals and Alloys. 163**
Jae-Joong RYU and Pranav SHROTRIYA

5.1. Introduction	164
5.1.1. Total joint replacements	167
5.1.2. Metal alloys.	169
5.2. Clinical studies and mechanistic investigation into implant failure.	173
5.2.1. Wear mechanisms	176
5.2.2. Physiological corrosion of metals	178
5.2.3. Bio-tribo-corrosion at the modular interface	180
5.2.4. Adverse effects due to the creation of wear particles	183

5.3. Residual stress development by rough surface contact.	184
5.3.1. Surface properties of bio-implants	186
5.3.2. Stress-assisted electrochemical dissolution and local corrosion damage	188
5.4. Conclusion	192
5.5. Bibliography	193
List of Authors	197
Index	201

Preface

In general, we currently define wear as the “progressive loss of material from the operating surface of a body occurring as a result of relative motion at the surface”. Wear is related to surface interactions, and more specifically to the form of contact due to relative motion. It is important to distinguish between mechanical wear and other processes with similar outcomes. For example, the current definition does not include:

- impact wear, where there is no relative motion;
- cavitation, where the counterbody is a fluid;
- corrosion, where the damage is due to chemical rather than mechanical action.

The progressive loss of material from surface is rarely catastrophic but it does reduce the operating efficiency of equipment, components and structures.

The purpose of this book is to present a collection of examples illustrating the state-of-the-art and research developments into the wear of advanced materials in several applications.

Chapter 1 presents tribological aspects of carbon fabric-reinforced polymer composites.

Chapter 2 covers the adhesive wear characteristics of the natural fibers of reinforced composites.

Chapter 3 contains information on resistance to cavitation (material selection).

Chapter 4 is dedicated to the cavitation of biofuel applied in the injection nozzles of diesel engines.

Finally, in Chapter 5, the wear and corrosion damage of medical-grade metals and alloys is presented.

The present book can be used as a research book for a final undergraduate engineering course (for example into materials, mechanics, etc.) or as the focus of the effect of wear on advanced materials at the postgraduate level. This book can serve also as a useful reference for academics, biomaterials researchers, mechanical and materials engineers, professionals in related spheres working with tribology and advanced materials. The interest in and the use of the topics covered in this book is evident for many important centers of research, laboratories and universities throughout the world. Therefore, it is hoped that this book will encourage and enthuse others to carry out research in this important field of science and engineering.

I would like to pass on my gratitude to ISTE-Wiley for this opportunity to expand the knowledge of others through the use of this book and I thank them for their professional support. Finally, I would like to thank all of the authors who worked on the various chapters for their work on this project.

J. Paulo Davim
University of Aveiro, Portugal
January 2012

Chapter 1

Carbon Fabric-reinforced Polymer Composites and Parameters Controlling Tribological Performance

The inclusion of carbon fiber reinforcement in composites in order to achieve high performance is currently one of the most attractive solutions when encountering increasing demands on the development of materials as a consequence of innovations in technology. Bidirectional reinforcement, as in the case of fabric, is preferable to the use of unidirectional or short fibers because of the possibility of higher specific strength in both directions and the ease of handling reinforcement during processing.

The performance of such composites is a result of various parameters, mainly related to their development and situations in which they are used under selected operating parameters. In the case of tribology, carbon fiber has special importance as reinforcement. This is especially the case in

2 Wear of Advanced Materials

polymers because of their additional important features, such as lubricity and high thermal conductivity and stability.

The main parameters responsible for the performance of such composites during development are:

- type of matrix and its molecular weight;
- type of carbon fibers (polyacrylonitrile [PAN], pitch etc., or strands, tows, etc.);
- amount of fabric and its weave;
- orientation of fiber/fabric with respect to loading direction;
- fiber–matrix interface;
- processing technique;
- various parameters.

In spite of lot of work reported on carbon fabric-reinforced polymer composites, no in-depth information presenting an overview of such composites is currently available.

This chapter provides a comprehensive review of the parameters of such composites and their influence on performance properties (mechanical and tribological in various wear modes) is presented by our development of a number of composites by varying one parameter at a time. It is concluded that the above-mentioned parameters significantly control the performance of composites. The influence of parameters on tribological properties does, however, depend on the modes of wear that are selected. In this chapter, we show that reinforcement proves significantly beneficial for adhesive and fretting wear situations; whereas in abrasive and erosive situations it proves detrimental.

1.1. Introduction to polymeric tribo-composites

From the tribological point of view, polymers have key features such as self-lubricity, resistance to wear (in dry conditions), corrosion, impact and shocks. Apart from ease in processing of components, they offer quiet operation because of very good damping capabilities. Polymeric tribo-composites also have serious limitations, such as low thermal stability, low strength and deterioration at elevated temperatures. Hence, they are almost invariably used in a composite form.

These composites are used in a variety of tribo-applications, such as ball bearings, cages, bushes, marine equipment, etc., and in load-bearing applications, such as struts, chassis and brackets in automotive and aircraft structures. This is because of their high flexural modulus, compressive strength and high resistance to corrosion [DOS 87]. In the aerospace industry, potential uses of composites containing graphite and carbon fibers include:

- their use as liners for self-aligning plain spherical bearings, cages and braces for ball and roller bearings;
- their use as a seal material for sliding-contact seals, piston rings, valves, bearings in copiers, business machines, space vehicle components, etc. [FUS 88].

Composites contain various constituents, such as fibers, fillers and solid lubricants of various types and sizes. Fibers generally increase load-carrying capacity and strength, and reduce the extent of the interaction of a polymer with the counterface, and hence reduce wear. Fibers are far more resistant to wear than the matrix, and the wear of fiber-reinforced polymers (FRPs) is mainly controlled by fibers. The role of the matrix is to hold the fibers firmly in adverse conditions involving thermal and mechanical stresses. The performance of FRPs depends mainly on the type of fiber/s and matrix, concentration, distribution, aspect ratio,

4 Wear of Advanced Materials

alignment with respect to loading direction, its adhesion to the matrix, processing technology, etc. Fibers with a high aspect ratio (l/r , where l and r are the length and radius of a fiber), have less chance of a concentration of flaws on their surface during loading, which effectively improves the rate of load transferred from the matrix to the fiber and hence the wear resistance of composites, W_R (inverse wear rate) [FRI 86].

$$\sigma_f = 2\tau l r^{-1} + \sigma_m \quad [1.1]$$

where:

- σ_f is the contact stress;
- σ_m is the compressive stress of the matrix in the composite loaded against a counterface under a load W ;
- τ is the tangential stress produced because of the difference in the moduli of a matrix and the fiber.

FRPs are mainly of two types – short fiber-reinforced polymers (SFRPs) and continuous fiber-reinforced polymers (CFRPs). Table 1.1 indicates the range of tribo-potentials and the application areas of such composites, including those of thin-layer composites. In the case of CFRPs, various possibilities exist, such as:

- unidirectionally reinforced with long fibers (UD);
- bidirectionally reinforced with woven or non-woven fabric (BD);
- three- or multi-directionally reinforced with the proper arrangement of fibers/fabrics in three or more directions (TD/multi-D).

Among these, SFRPs are the easiest to manufacture, with a very high production rate through injection molding. However, such SFRPs have comparatively lower

tribo-potential properties and strength (Table 1.1), while UD composites have moderate potential.

The manufacturing of composites is not carried out by injection molding, but by compression molding in general. Processing is very difficult in the case of UD composites basically because of the difficulties involved in handling the fibers. BD reinforcement is the most promising because of its multiple advantages, such as its very good strength properties in both directions and ease of fiber handling during processing.

Among the three classes of polymers, known as elastomers, thermosets and thermoplastics; thermosets such as epoxies are the most favoured for manufacturing BD composites with carbon fabric for lightweight construction parts, especially in the aircraft industries basically because they have a very good cost-to-performance ratio. For tribo-components, however, such polymers have not proved the right choice because of lower thermal stability and the higher μ offered by epoxies/thermosets. Instead, thermoplastics have proven a better choice, mainly because of their higher thermal stability, as in the case of specialty polymers such as polyimides, polyetherimide (PEI), polyetheretherketone (PEEK), polyethersulfone (PES), polytetrafluoroethylene (PTFE), etc., high damping capacity, better tribo-performance and the possibility of reusing the polymer.

Among the most favored tribo-fibers – glass, carbon and Aramid – glass fibers are the cheapest and are moderately effective in reducing wear but generally affect the μ adversely. Carbon/graphite fibers are the most expensive. They are highly effective in reducing both friction and wear, and also act as thermal conductivity boosters. Aramid fibers, on the other hand, are moderate in cost and effective in reducing wear and sometimes also friction. Thus, in spite of

6 Wear of Advanced Materials

their high cost, carbon fabric is the most favoured reinforcement for composites, including tribo-composites, where performance is the decisive parameter rather than the cost [SOU 05].

Composite material	Tribo-applications	Applicable operating parameters (pv, v and T)	Maximum tribological potential
Neat and SFRPs	Seals, gears, slideways bearings, mild abrasive wear applications, etc.	$pv < 15 \text{ MPa.m/s}$ $v < 5 \text{ m/s}$, $T < 250^\circ\text{C}$	$\mu > 0.03$ $K_0 > 10^{-16} \text{ m}^3/\text{Nm}$
CFRPs (UD and BD composites)	Under-water or high-temperature applications, aerospace seals, bearings, etc.	$pv < 100 \text{ MPa.m/s}$ $v < 5 \text{ m/s}$ $T < 320^\circ\text{C}$	$\mu > 0.09$ $K_0 > 10^{-17} \text{ m}^3/\text{Nm}$
Thin-layer composites with metallic supports	High-pressure applications, pivot bearings etc.	$pv < 300 \text{ MPa.m/s}$ $v < 1 \text{ m/s}$ $T < 320^\circ\text{C}$	$\mu > 0.06$ $K_0 > 10^{-18} \text{ m}^3/\text{Nm}$

Key: p – pressure, v – speed, T– temperature, and K_0 – specific wear rate

Table 1.1. *Tribo-potential of polymers and composites for a variety of applications [FRI 93]*

1.2. Carbon fibers as reinforcement

Carbon fibers (about 5–10 μm in diameter with a density of around 1.78 g/cc) predominantly consist of carbon atoms. They have special properties, such as:

- an exceptionally high tensile strength-to-weight ratio;
- high reinforcing capability;

- very low coefficient of linear thermal expansion, which provides good dimensional stability;
- high fatigue strength;
- high thermal conductivity;
- lubricity;
- wear-reducing capability.

They also have some limitations [MAL 08, DON 96, CHU 94, BUN 88, CHO 93, BUR 99, MOR 05], such as:

- low strain-to-failure values;
- low impact resistance;
- higher electrical conductivity, which may cause a short-circuit in unprotected electrical machinery.

The major areas for the application of carbon fibers are shown in Table 1.2.

The atomic structure of carbon in fiber form is similar to that of graphite (a crystalline material), consisting of sheets of carbon atoms called graphenes arranged in a regular hexagonal pattern.

The sheets are stacked parallel to one another in a regular fashion. The intermolecular forces between the sheets (Van der Waal forces) are relatively weak, giving graphite its soft and brittle characteristics. The crystallographic structure provides the attributes of higher tensile strength and modulus in the direction that is normal to the graphene sheets.

1.2.1. *Classification of carbon fibers*

Carbon fibers are commercially available in varying ranges of tensile modulus (237 to 1,035 GPa). Lower

8 Wear of Advanced Materials

modulus fibers have a lower density, lower cost, higher tensile and compressive strength, and higher strain-to-failure ratios.

Physical strength, specific toughness, light weight	Aerospace, road and marine transport, sporting goods, etc.
High dimensional stability, low coefficient of thermal expansion, low abrasion	Missiles, aircraft brakes, aerospace antenna and support structure, large telescopes, optical benches, waveguides for stable high-frequency (GHz) precision measurement frames, etc.
Good vibration damping, strength and toughness	Audio equipment, loudspeakers for hi-fi equipment, pickup arms, robot arms, etc.
Electrical conductivity	Automobile hoods, novel tooling, casings and bases for electronic equipment, EMI (electromagnetic interference) and RF (radio frequency) shielding, brushes, etc.
Biological inertness and X-ray permeability	Medical applications in prostheses, surgery and X-ray equipment, implants, ligament repair, etc.
Fatigue resistance, self-lubrication, high damping	Dry bearing applications
Chemical inertness, high corrosion resistance	Chemical industry; nuclear field; valves, seals, pump components in process plants, etc.
Electromagnetic properties	Large generator retaining rings, radiological equipment, etc.

Table 1.2. *Properties and applications of carbon fibers ([MAL 08], www.chem.wisc.edu, www.netcomposites.com)*

Carbon fibers are manufactured from synthetic fibers through heating and stretching processes. Depending upon the fiber precursor materials, carbon fibers may be turbostratic or graphitic, or mixed. In turbostratic carbon fibers, the sheets of carbon atoms are haphazardly folded or crumpled. Carbon fibers derived from PAN are turbostratic,