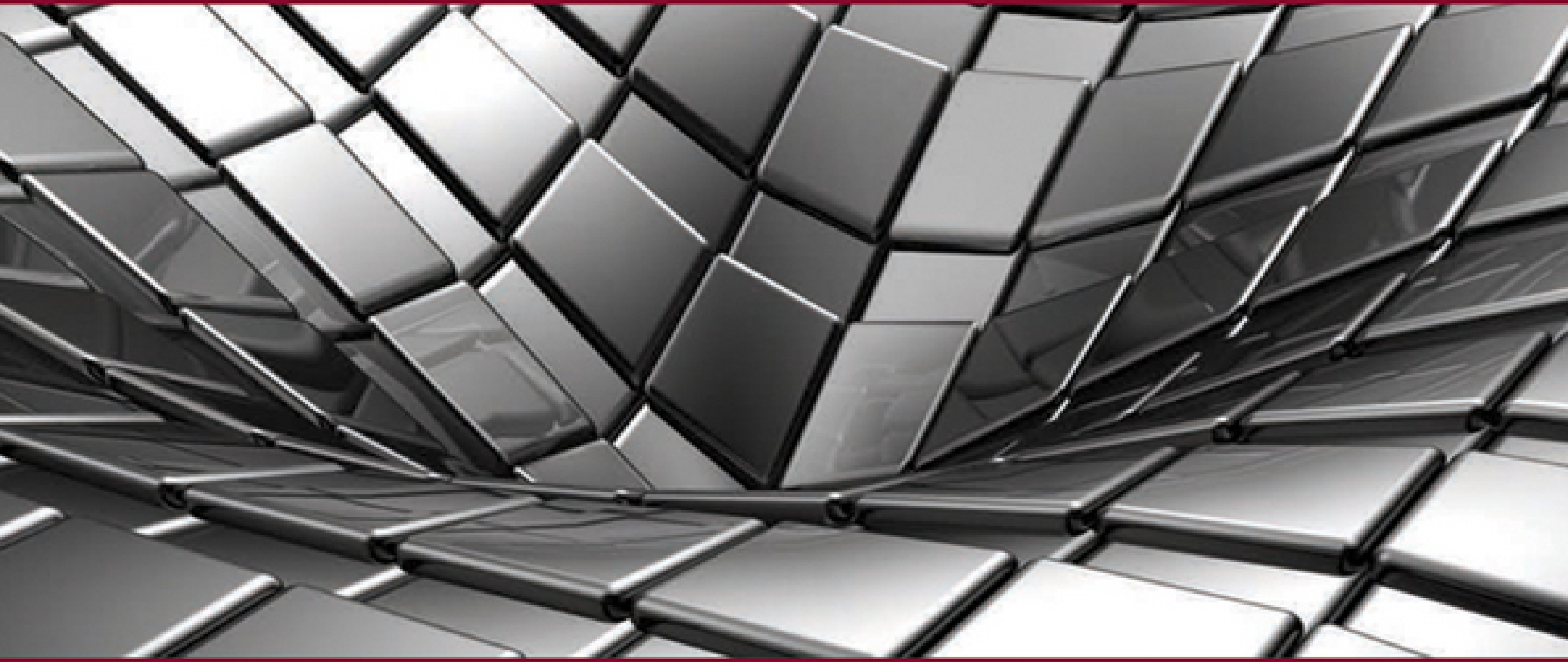

Wear of Advanced Materials

Edited by
J. Paulo Davim

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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 fabricreinforced 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.

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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 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 tribocomposites 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 triboapplications, 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 fiberreinforced 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, 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].

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

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).

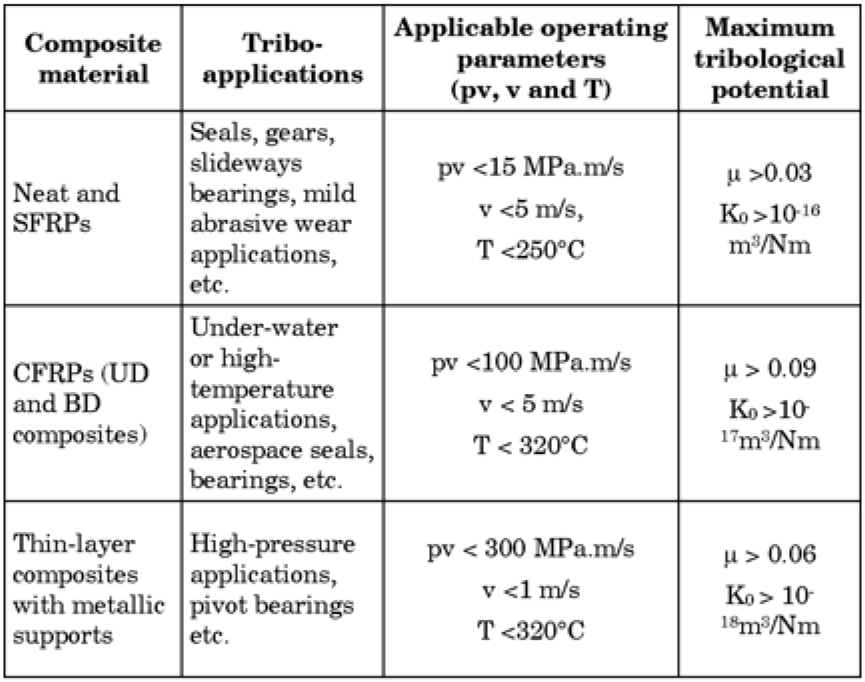
Among these, SFRPs are the easiest to manufacture, with a very high production rate through injection molding. However, such SFRPs have comparatively lower tribo-potential properties and strength (Table 1.1), while UD composites have moderate potential.

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), ppolyethersulfone (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 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].

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



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 MPa.m/s v <5 m/s, T <250°C	$\mu > 0.03$ $K_0 > 10^{-16}\ m^3/Nm$
CFRPs (UD and BD composites)	Under-water or high-temperature applications, aerospace seals, bearings, etc.	pv <100 MPa.m/s v < 5 m/s T < 320°C	$\mu > 0.09$ $K_0 > 10^{-17}\ m^3/Nm$
Thin-layer composites with metallic supports	High-pressure applications, pivot bearings etc.	pv < 300 MPa.m/s v <1 m/s T <320°C	$\mu > 0.06$ $K_0 > 10^{-18}\ m^3/Nm$

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

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

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

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, selflubrication, 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.

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, whereas carbon fibers derived from the mesophase pitch followed by heat treatment at temperatures exceeding 2,200°C are graphitic. Turbostratic carbon fibers tend to have high tensile strength, whereas heat-treated mesophasepitch- derived carbon fibers have high Young’s modulus and thermal conductivity. Based on precursor fiber material, modulus, strength and final heat treatments, carbon fibers are classified into the categories given below ([MAL 08], www.cytec.com, www.netcomposites.com).

1.2.1.1. *Fiber precursor*

Based upon the precursor material used, the carbon fibers are classified as PAN-based, pitch-based, mesophase pitchbased, isotropic pitch-based, rayon-based, gas-phase grown, etc.

1.2.1.2. *Fiber properties*

Based upon the carbon fiber properties, the classifications include those with:

– ultra-high modulus (UHM) with >450 GPa;

– high modulus (HM) with 350–450 GPa;

– intermediate modulus (IM), with 200–350 GPa;

– low modulus and high tensile (HT), with <100 GPa, tensile strength and >3.0 GPa;

– super-high tensile (SHT) with tensile strength >4.5 GPa.

1.2.1.3. *Final heat treatment*

Based upon the final heat treatment, the carbon fibers are classified as:

– High heat-treatment (HHT) carbon fibers, where the final heat treatment temperature should be >2,000°C and can be associated with a high-modulus type fiber.

– Intermediate heat-treatment (IHT) carbon fibers, where the final heat treatment temperature should be around or above 1,500°C and can be associated with a high-strength type fiber.

– Low heat-treatment (LHT) carbon fibers, where the final heat treatment temperatures are no higher than 1,000°C. These are low-modulus and low-strength materials.

PAN, pitch and rayon are the main raw materials used to produce carbon fibers.

PAN precursors form the basis of the majority of commercially-available carbon fibers and general have higher tensile strengths. These precursors can be thermally modified before decomposition, which allows them to be oxidized and stabilized before the conversion process to carbon fibers, while maintaining the same filamentary configuration. Pitch precursors are based on petroleum asphalt, coal tar and polyvinyl chloride.

Pitches are relatively low in cost and high in carbon yield.

Rayon precursors are derived from cellulosic materials. The high weight loss and low conversion yield to carbon fibers is the main processing disadvantage. Typically only 25% of the initial fiber mass turns into fibers after carbonization, making them more expensive to produce.

The tensile strength of carbon fibers can be increased by hot stretching >2,000°C, during which graphitic planes are aligned in the filament direction. The high modulus of pitch fibers is due to the fact that they are more graphitizable and the shear between parallel planes of the graphitized fiber is easier. These are more sensitive to defects and flaws, and their tensile strength is not as high as that of PAN fibers (in which graphitic basal planes are parallel to the fiber axis) [MAL 08]. The difference in structure of these two types of fibers is shown in Figure 1.1. Table 1.3 gives the typical properties of PAN- and pitch-based carbon fibers.

Figure 1.1. *Graphitic structure of a carbon fiber*

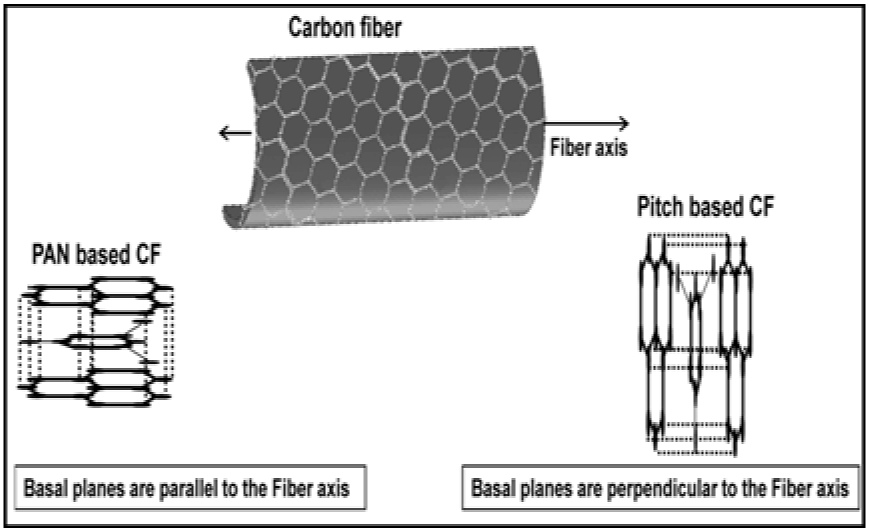


Table 1.3. *Typical properties of PAN- and pitch-based carbon fibers [KEL 94, MAL 08]*

Properties/fiber type	PAN-based	Pitch-based
Thermal conductivity (W/mK)	10–100	20–1000
Electric conductivity (S/m)	10^4–10^5	10^5–10^6
Specific heat (at 300 K)	0.17	0.17
Density (g/cc)	1.76	1.90
Tensile strength* (MPa)	434	220
Tensile modulus* (GPa)	235	380

*varies with the type of heat treatment