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Tribology of Polymeric Nanocomposites

Klaus Friedrich
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Friction and Wear of Bulk Materials and Coatings

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Vol. 42 Lubricated Wear – Science and Technology (Sethuramiah)
Vol. 43 Transient Processes in Tribology (Lubrecht, Editor)
Vol. 44 Experimental Methods in Tribology (Stachowiak and Batchelor)
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Aims & Scope

The Tribology Book Series is well established as a major and seminal archival source for definitive books on the subject of classical tribology. The scope of the Series has been widened to include other facets of the now-recognised and expanding topic of Interface Engineering.

The expanded content will now include:
• colloid and multiphase systems; • rheology; • colloids; • tribology and erosion; • processing systems; • machining; • interfaces and adhesion; as well as the classical tribology content which will continue to include • friction; contact damage; • lubrication; and • wear at all length scales.

FOREWORD

The area of tribology deals with the design, friction, wear and lubrication of interacting surfaces in relative motion. Polymer composite materials have been used increasingly for such tribological applications in recent years. Yet, by now, much of the knowledge on their tribological behavior is often empirical, and very limited predictive capability currently exists. Nevertheless, it has been attempted in several books and scientific papers of the last two decades to determine to what degree phenomena governing the friction and wear performance of polymer composites can be generalized (see e.g. refs. [1–5] and references therein).

Within the past 10 years, many developments of new polymers composites have incorporated nanofillers as reinforcing agents, resulting in the term "polymeric nanocomposites". In fact, it has been demonstrated that these fillers of very small dimension (as compared to the classical micrometer-sized fibers or particles) can also result in remarkable improvements in the friction and wear properties of both bulk materials and coatings. Therefore, it is the intention of this book to give a comprehensive description of polymeric nanocomposites, both as bulk materials and as thin surface coatings, and their behavior and potential use in tribological applications. The preparation techniques, friction and wear mechanisms, properties of polymeric nanocomposites, characterization, evaluation and selection methodology in addition to application examples will be described and discussed. One aim of the book is to bring together, systematically in a single volume, the state-of-the-art knowledge on the tribology of polymeric nanocomposites and coatings. This has previously been difficult to achieve and overview because the information has only been available in the form of numerous separate articles not linked logically together.

More than 20 groups of authors worldwide, many of them well known in the tribology community since years, have agreed to write down their particular expertise on nanocomposites' tribology in individual chapters. The latter cover not only different types of polymer matrices, i.e. from thermosets to thermoplastics and elastomers, but also a variety of micro- and nanofillers, from ceramic nanoparticles to carbon nanotubes, in combination with traditional tribo-fillers, such as short carbon fibers, graphite flakes and polytetrafluoroethylene (PTFE) particles. The coatings can be prepared on ceramic metallic or polymeric substrates and applied in many different applications, including automotive, aerospace and mechanical engineering.

In Chapter 1 by Briscoe and Sinha, in which tribological trends for polymer composites, both traditional and nanocomposites, are presented, using data currently available in the literature, the book is structured into four main sections. The first one is dedicated to the tribology of bulk polymer composites against metallic counterparts, with particular emphasis to the use of spherical nanoparticles. S. Bahadur and C. J. Schwartz report on the influence of nanoparticle fillers in polymer matrices on the formation and stability of transfer films during wear. Synergistic effects of nanoparticles and traditional fillers on the sliding wear of polymeric hybrid composites are discussed by L. Chang et al. In more detail, Q. Wang and X. Pei illustrate that the volume content, the size and the shape of the nanoparticles may exert a great influence on the friction and wear behavior of various polymer matrices. In the following chapter by Pesetskii, Bogdanovich and Myshkin, special emphasis is focused on the tribological behavior of thermoplastic nanocomposites, containing as fillers carbon nanomaterials, layered clays, metals and metal-containing compounds. Sliding wear of thermosetting nanocomposites based on an epoxy resin matrix is, on the other hand, the topic of the contribution by M. Q. Zhang and his group. In the conclusion of this section, L. Kónya and K. Váradi present some wear simulation studies of a polymer–steel sliding pair by considering temperature and time-dependent material properties.

The second section of this book concentrates on the use of carbon nanotubes and nanofibers as reinforcements in bulk nanocomposites against metallic counterparts. Ruckdäschel, Sandler and Altstädt give a comprehensive overview on the friction and wear of carbon nanofiber-reinforced PEEK-based polymer composites. Based on their promising results, the performance of advanced nanocomposite hybrid materials for an intended industrial tribological application is discussed. The chapter of O. Jacobs and B. Schädel elucidates the effect of carbon nanotube reinforcement on the sliding wear of epoxy resin and of ultra high molecular weight polyethylene against two different steel counterparts. It also shows that the dispersion method of the carbon nanotubes has a remarkable influence on the tribological properties. Finally, the friction and wear characteristics of randomly dispersed vs. well-aligned carbon nanotubes in two different matrices, i.e. epoxy vs. carbon, is outlined by Q. Gong et al.

The third main section of this book relates to the problem of scratch/wear resistance of nanocomposites and their coatings. In the spirit of the now-classical treatment of mechanical data in the form of fracture and failure maps, K. Kato describes, in general, wear and corresponding wear maps of hard coatings. In the following, E. Iwamura introduces two types of hybridized carbon films with different nanocomposite configurations with regard to their tribological properties. In particular, the structurally modified column/inter-column films showed a high wear resistance in spite of a distinctively poor film hardness. Some new developments in the field of wear of "nanomodified" rubbers and their coatings, studied under three different test configurations, are presented in the chapter of J. Karger-Kocsis and D. Felhös. It is the intention to use these new developments in automotive seal applications. Another coating material, i.e. sol–gel coatings on polymer substrates, has been widely used in optical lenses, safety windows and flexible display panels. Z. Chen and L. Y. L. Wu review in their chapter the scratch failure modes of such coatings on polymeric substrates, the related failure mechanisms and the parametric models related to these failure modes. A new scratch testing and evaluation method is presented by R. L. Browning, H. Jiang and H.-J. Sue. The potential of this procedure is demonstrated with regard to the scratch behavior of acrylic coatings and epoxy nanocomposites. Finally, a wide survey of the existing literature on scratch and wear damage in polymer nanocomposites, followed by own results on the scratch behavior of various nanoclay and other nanoparticle-filled polymer systems, is given by A. Dasari, Z.-Z. Yu and Y.-W. Mai.

In the fourth section, chapters are found which especially focus on the tribological use of naocomposites and their coating for special applications. The group of W. G. Sawyer gives a comprehensive review on the development of PTFE matrix nanocomposites for the use of these systems in moving mechanical devices. A. Gebhard, F. Haupert and A. K. Schlarb report about the application of nanostructured slide coatings for automotive components, such as engine piston skirts and polymer/metal-slide bearings. A special topic, namely the friction and wear of nanoparticle-filled PEEK and its composite coatings applied by flame spraying or painting on metallic parts, is described by G. Zhang, H. Liao and C. Coddet. In a more traditional composite-processing method, Bijwe, Hufenbach, Kunze and Langkamp report about the development of polymer composite bearings with engineered tribosurfaces. They can be used in extreme conditions of temperature (cryogenic to 300 °C), vacuum to high-pressure environment, especially where liquid lubrications cannot be considered. On the contrary, well-lubricating coating and thin film applications are the focus of the chapter by N. R. Choudhury, A. G. Kannan and N. Dutta. The materials are organic–inorganic hybrids, their methods of preparation, their relevance to biomaterials' friction, their fundamental mechanics of tribology and the lubrication mechanisms of such coatings and thin films.

When considering the content of this book as a whole, it becomes clear that it is primarily intended for scientists in academia and industry, who are involved or want to become involved in tribology problems, and who look for new solutions in materials' development and for particular applications. The book will be, therefore, a reference work and a guide to practice for those who are or want to become professional in the field of polymer composites tribology.

By preparing this book, we hope that we have managed to take the first step toward a systematic structure in this complex field of technology. At the same time, we believe that this is timely, but only a first attempt to cover a topic that is in the process of rapid development since the last couple of years. We are sure that many more interesting results on the tribology of nanocomposite materials will be published in the open literature in the near future.

Finally, we would like to thank all the contributors who managed to include their thoughts and results in this special book. We are also grateful to many other scientists who made their contributions by taking part in the extensive peer-reviewing process. These reviewers include:

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CONTENTS

PART II: USE OF CARBON NANOTUBES IN BULK COMPOSITES

PART III: SCRATCH/WEAR RESISTANCE OF NANOCOMPOSITES/COATINGS

PART IV: DEVELOPMENTS OF NANOCOMPOSITES/COATINGS FOR SPECIAL APPLICATIONS

CHAPTER 1

Tribological applications of polymers and their composites: Past, present and future prospects

Brian J. Briscoe and Sujeet K. Sinha

Contents

Abstract

This chapter presents a brief account of the current state-of-the-art in the area of the tribology of polymers and their composites. The classical explanation of friction based upon the "two-term model" is presented. Further, important factors affecting friction and wear of polymers from the design and materials selection perspectives are described in detail. Tribological trends for polymer composites, both traditional and nanocomposites, are presented using data currently available in the literature. Finally, based on our current understanding of this field, we have speculated upon some future trends and directions in the area of polymer tribology. Our assessment is naturally very subjective and selective given the vast potential for research growth in this field.

This review is not meant to be exhaustive, and hence readers will naturally need to refer other chapters presented in this book for a much more detailed knowledge of the area of polymer tribology in general and tribology of nanocomposites in particular.

1.1 Introduction

Polymers play an important part in materials and mechanical engineering, not just for their ease in manufacturing and low unit cost, but also for their potentially excellent tribological performance in engineered forms [1]. In the pristine or bulk form, only a few of the polymers would satisfy most of the tribological requirements, however, in the composite and hybrid forms, polymers often have an advantage over other materials such as metals and ceramics. Polymer tribology, as a research field, is now well-mature given that roughly 50 plus years have seen publication of numerous research articles and reports dealing with a variety of tribological phenomena on a considerably large number of polymers, in bulk, composite and hybrid forms. Tribological applications of polymers include gears, a range of bearings, bearing cages, artificial human joint bearing surfaces, bearing materials for space applications including coatings, tires, shoe soles, automobile brake pads, non-stick frying pans, floorings and various types of surfaces for optimum tactile properties such as fibers. The list is growing. For example, in the new area of micro-electromechanical systems (MEMS), polymers (such as PMMA and PDMS) are gaining popularity as structural materials over the widely used material, Si [2]. Often, Si is modified by a suitable polymeric film in order to enhance frictional, anti-wear or anti-stiction properties [3].

Similar to the bulk mechanical responses, the tribological characteristics of polymers are greatly influenced by the effects of temperature, relative speed of the interacting surfaces, normal load and the environment. Therefore, to deal with these effects and for better control of the responses, polymers are modified by adding appropriate fillers to suit a particular application. Thus, they are invariably used in composite or, at best, in blended form for an optimum combination of mainly friction and wear performances. Also, pragmatically fillers may be less expensive than the polymer matrix. The composition of the filler materials, often a closely guarded secret of the manufacturer, is both science and art, for the final performance may depend upon the delicately balanced recipe of the matrix and filler materials. However, the past many years of research in the area of polymer tribology in various laboratories have shed much light into the mechanisms of friction and wear. This has somewhat eased the work of materials selection for any particular tribological application.

This chapter on the tribology of nanocomposite, an area which is still in its infancy, would endeavor to set the background of the research in polymer tribology. We will refer to the term "polymer" for synthetic organic solid in pristine form, with some additives but no fillers aimed at modifying mechanical properties. The word "composite" would be used when one or more than one filler has been added to a base polymer with the aim of drastically changing mechanical and tribological properties. "Nanocomposite" will mean a composite in which at least one filler material has one of its dimensions in the range of a few to several nanometers.

The chapter would review some of the past, but now classical, works when much of the mechanisms of friction and wear for general polymers were studied and these explanations have stood the test of the time. The early works led to the area of polymer composites where polymers were reinforced with particles and/or short or long fibers. Often, the use of the filler materials has followed two trends that mainly reflect the actual function that the fillers are expected to perform. This type of work on the design of multi-phase tribological materials continues mainly aimed at improving an existing formulation, or, using a new polymer matrix or novel filler. The present trend is expected to extend into the future but with much more refinement in materials and process selections. For example, the use of nano-sized particle or fibers coupled with chemical enhancement of the interactions between the filler and the matrix seems to produce better tribological performance. Also, there have been some very recent attempts on utilizing some unique properties of polymers, often mimicking the biological systems in one way or the other, which has opened up new possibility of using polymers in tribological applications. One example of this is the polymer brush that can be used as a boundary lubricant. This trend will definitely continue into the future with great promises for solving new tribological issues in micro, nano and bio systems.

1.2 Classical Works on Polymer Tribology

1.2.1 Friction

The earliest works on polymer tribology probably started with the sliding friction studies on rubbers and elastomers [4, 5]. Further work on other polymers (thermosets and thermoplastics) led to the development of the two-term model of friction [6]. The two-term model proposes that the frictional force is a consequence of the interfacial and the cohesive works done on the surface of the polymer material. This is assuming that the counterface is sufficiently hard in comparison to the polymer-mating surface and undergoes only mild or no elastic deformation. Fig. 1.1 shows a schematic diagram of the energy dissipation processes in the two-term model [7].

The interfacial frictional work is the result of adhesive interactions and the extent of this component obviously depends upon factors such as the hardness of the polymer, molecular structure, glass transition temperature and crystallinity of the polymer, surface roughness of the counterface and