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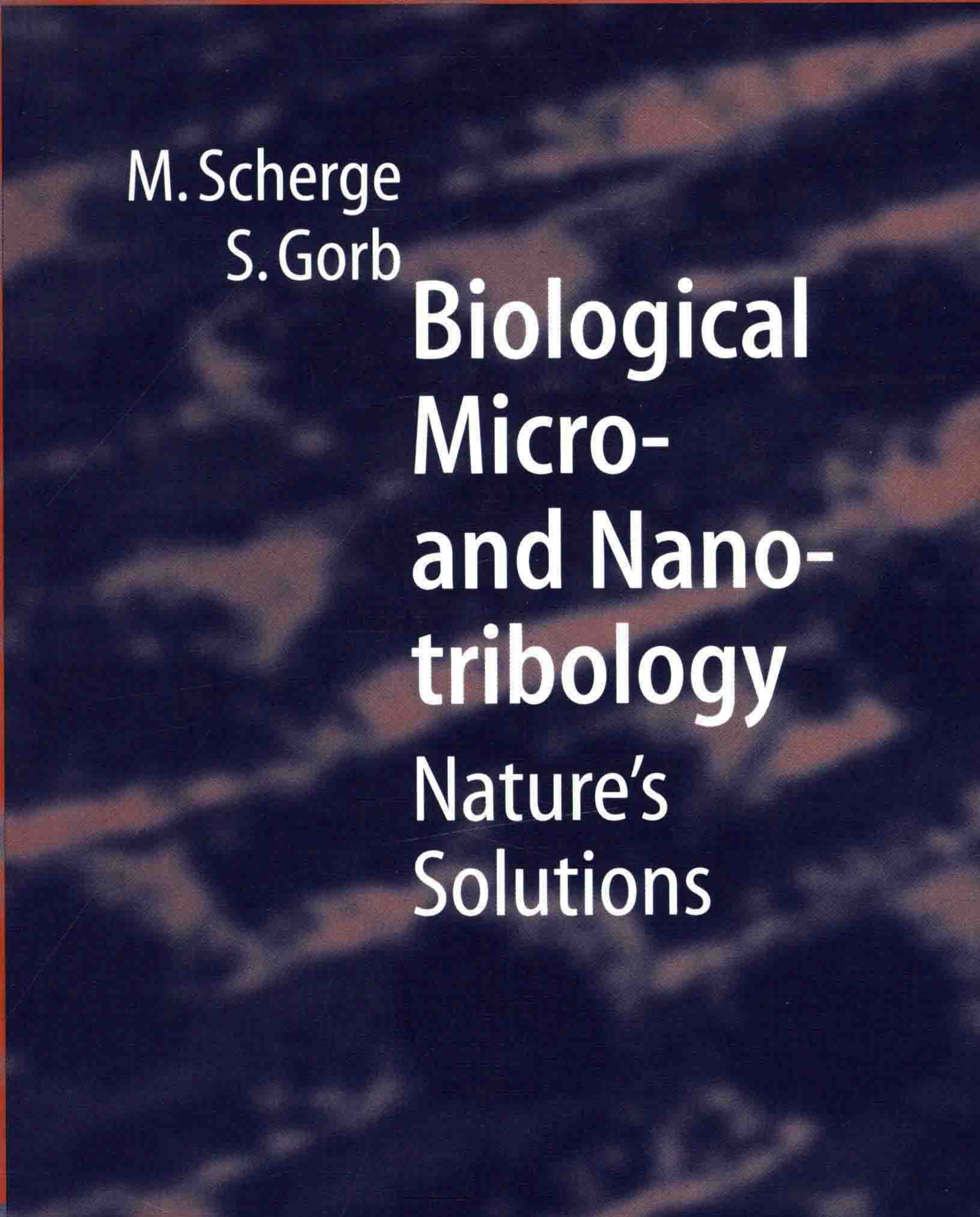

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Biological Micro- and Nano-tribology

Nature's Solutions

Springer

Matthias Scherge Stanislav N. Gorb

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With 164 Figures

Springer

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ISSN 1434-4904
ISBN 3-540-41188-7 Springer-Verlag Berlin Heidelberg New York

Library of Congress Cataloging-in-Publication Data.

Scherge, Matthias 1962– . Biological micro- and nanotribology / Matthias Scherge and Stanislav N. Gorb. p.cm. – (Nanoscience and technology). Includes bibliographical references and index. ISBN 3-540-41188-7 (alk. paper). 1. Tribology. 2. Nanotechnology. I. Gorb, Stanislav N., 1965– . II. Title. III. Series. TJ1075.S348 2001 621.8'9–dc21 00-066117.

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Springer-Verlag Berlin Heidelberg New York
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http://www.springer.de

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Printed in Germany

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Typesetting: Camera-ready by the authors using a Springer TeXmacropackage
Cover design: *design & production*, Heidelberg

Printed on acid-free paper SPIN: 10758150 57/3141/tr - 5 4 3 2 1 0

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Foreword

Ever since the genesis of life, and throughout the course its further evolution, Nature has constantly been called upon to act as an engineer in solving technical problems. Organisms have evolved a variety of well-defined shapes and structures. Although often intricate and fragile, they can nonetheless deal with extreme mechanical loads. Some organisms live attached to a substrate; others can also move, fly, swim and dive. These abilities and many more are based on a variety of ingenious structural solutions. Understanding these is of major scientific interest, since it can give insights into the workings of Nature in evolutionary processes. Beyond that, we can discover the detailed chemical and physical properties of the materials which have evolved, can learn about their use as structural elements and their biological role and function. This knowledge is also highly relevant for technical applications by humans.

Many of the greatest challenges for today's engineering science involve *miniaturization*. Insects and other small living creatures have solved many of the same problems during their evolution. Zoologists and morphologists have collected an immense amount of information about the structure of such living micromechanical systems. We have now reached a sophistication beyond the pure descriptive level. Today, advances in physics and chemistry enable us to measure the adhesion, friction, stress and wear of biological structures on the micro- and nanonewton scale. Furthermore, the chemical composition and properties of natural adhesives and lubricants are accessible to chemical analysis. And not least, computer-aided reconstructions can be exploited to mimic biomechanical systems in the workshop of the engineer.

The present book by Scherge and Gorb is devoted to biomechanical systems with frictional surfaces or adhesive secretions to attach parts of the body to each other, or to attach the organism to a substrate. Such systems have fascinated microscopists for centuries, but only recently has the use of novel methods enabled us to really understand the functioning of at least some of these systems. This book is an excellent example of interdisciplinary science in action, drawing as it does on approaches from physics, engineering, tribology, structural biology, and materials science. The text is not confined to the broad variety of natural devices adapted for attachment: In order to show the different principles of morphology, ultrastructure and biomechanics of friction systems, it also presents several examples of experiments and outlines the general rules governing the interrelationship between the design of biological structures, their properties, and their functions. This account is based on knowledge accumulated in long-term studies of the principles of microtribology *(Scherge)* and ultrastructural and experimental studies of insect attachment devices *(Gorb)*. It provides a first-class introduction to the principles of biological micro- and nanotribology. Together with the data on ultrastructure, material properties, and attachment–detachment performances of biological frictional systems, the book is an excellent starting point for engineers and physicists working with biological systems and for biologists starting to study friction and adhesion. The information presented will undoubtedly also be useful in areas of high-technology, such as micromechanics and the science of composite materials.

Max Planck Institut für
Entwicklungsbiologie, September 2000

U. Schwarz

Preface

This book is intended for scientists and engineers who want to become familiar with biological micro- and nanotribology as a new interdisciplinary field of research combining methods and knowledge of physics, chemistry, mechanics and biology. The aim of biological micro- and nanotribology is to gather information about friction, adhesion and wear of biological systems and to apply this new knowledge to the design of Micro–Electro–Mechanical Systems, the development of monolayer lubricants, the development of new adhesives, or the construction of artificial joints.

The book is divided into five main sections, where the first part is titled **Basics and Physical Tools**, the second part **Biological Friction Systems**, the third part **Test Equipment**, and the fourth part **Case Studies**. The last part contains the **Appendix**.

The first part deals with basic subjects such as microfriction and adhesion theory and measurement, and the applicability and usage of contact models, as well as lubrication. Especially emphasized is the action of thin liquid films and their influence on adhesion and friction. A detailed study is devoted to water, since this is the most common adsorbate film. The tribological properties are explained using a silicon ball sliding on a flat silicon sample. This system is treated as a model and reference system to provide a platform on which the data obtained from the biological tests can be interpreted.

The second part deals with explicit studies of biological friction and adhesion phenomena, where the fundamental problems are discussed. An overview on biological friction and adhesion systems is given. From studies of biological macrotribology (human joints, etc.), the field of biological microtribology will be defined. As they appear in the text, the biological terms are explained. For more information the reader can make use of the glossary at the end of the book.

In the third part technical equipment is introduced. A detailed description is devoted to novel test equipment to take account of recent major advances in measurement and characterization. Modern instruments are introduced, including laser interferometer- and fiber-optics-based microfriction and adhesion testers and scanning probe microscopes. This part also focuses on biological preparation techniques applied to maximize the outcome of the experiments. In addition, supporting technical analysis methods like microscopy

(SEM, TEM), chemical analysis (for example photoelectron spectroscopy) and thin film characterization are discussed.

Topics discussed in the fourth part of the book are special case studies performed with the great green bush cricket (*Tettigonia viridissima*). This part combines the knowledge of Parts I, II and III to analyze friction, indentation and adhesion between the attachment pads of the cricket and various kinds of substrate. Attention is paid also to the problems of sample aging and stability of the test parameters.

Biologists, chemists, physicists and tribologists and many other applied scientists will find this book a useful addition to their libraries. Moreover, this book is intended as an introduction to the higher levels of micromechanical analysis and is well suited for, for example, graduate students who want to become active in interdisciplinary research. The majority of the sections close with an itemized summary of the most important results.

We wish to express our gratitude to I.U. Ahmed, J. Berger, S. Granick, H.J. Haefke, J. Halbritter, Y. Jiao, V. Kastner, J.A. Schaefer, M. Schoen, U. Schwarz and H. Schwarz for their fruitful discussion and help. Additional thanks go to A. Lahee and C. Ascheron of Springer-Verlag as well as to G. Hartung, G. Hungenbach, X. Li, A. Opitz and R. Nevchoupa for improving the text. We would also like to thank K. von Klitzing and R. Wiesendanger for giving us the opportunity to publish in the "NanoScience and Technology" series.

Special thanks go to our families for their love and support.

Karlsruhe
Tübingen
January 2001

M. Scherge
S. N. Gorb

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Part I

Basics and Physical Tools

1. Introduction

Micro- and nanotribology – considered as the mechanical interaction of moving bodies – is the science of friction, adhesion, lubrication and wear on the length scale of micrometers to nanometers and the force scale of millinewtons (mN) to nanonewtons (nN). This rather young field of (micro- and nano-) science was boosted by the advent of new analysis techniques, for example the Atomic Force Microscope (AFM), allowing insight into fundamental processes. In the microrange the data storage industry used tribology to solve problems concerning the head–disk–interface in magnetic disk drives. Due to miniaturization of the mechanical parts the forces at the interface decreased dramatically and have reached the nanorange for the case of IBM's millepede, an AFM-based storage device [1]. More and more conventional mechanical devices, for instance motors [2], are becoming miniaturized. Former mesoscale applications like accelerometers in cars are being replaced by silicon-based mechanical microsystems (see [3] for an overview).

Biological insect microsystems and technical microsystems have many things in common. First of all, the mechanical interaction occurs on identical length and force scales [4,5]. In both types of system surface properties, for example wettability, microstructure or surface chemistry, have a strong impact on the performance of the system. In a few cases biological design examples were used for technical systems, as shown in Fig. 1.1 [6]. Here, the technical microsystem adopts the friction-induced motion of a worm. Internal microdrives accomplish a harmonica-like motion of the "techno-insect".

Whereas the mechanical properties of technical microsystems with respect to friction and adhesion are mainly determined by the physico-chemical state of the topmost atomic layers of the solid, biological microsystems are also strongly influenced by contributions of the bulk due to their elastic and viscoelastic constitution.

The other main difference between biological and technical microsystems is their performance. While insect micromechanics always operates in a lubricated state, no reliable concepts exist for technical microsystems. For example, the joints of the cricket, shown in Fig. 1.2, are lubricated. In contrast, the application of a liquid to a micromechanical gear system would prevent the whole system from operating, since capillary action induces forces higher