Michelle Lee
Editor

Remarkable Natural Material Surfaces and Their Engineering Potential

Springer

Remarkable Natural Material Surfaces and Their Engineering Potential

Michelle Lee
Editor

Remarkable Natural Material Surfaces and Their Engineering Potential

Springer

Editor
Michelle Lee
Mechanical Engineering
McCormick School of Engineering
at Northwestern University
Evanston, IL, USA

ISBN 978-3-319-03124-8 ISBN 978-3-319-03125-5 (eBook)
DOI 10.1007/978-3-319-03125-5
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014930576

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

It is my great pleasure to introduce to you this book that contains a series of articles about the surfaces of several species in our natural world.

We are luckily living on the only blue globe in the universe so far understood by modern astronomy, sharing the same blue sky and water with other species also

Dikilitaş, in *Sultanahmet Meydanı*, Istanbul, Turkey, an example showing the inspiration from nature on human society civilization nursed by planet Earth. At the same time that we enjoy our bread and butter, we admire the awesome power of nature that has created the rich, beautiful, and complicated yet mysterious botanic, marine and animal systems.

Thousands of years of human civilization has only explored small corners of the mighty natural world formed through millions of years of evolution. Nature demonstrates its laws peacefully and gracefully sometimes, but loudly at other times. Ancient Greeks showed their admiration of nature by creating gods related to natural powers. The ancient Egyptian language is among the oldest languages; it uses many symbols from nature. A good example is *Dikilitaş*, or the Obelisk of Theodosius, which was the Ancient Egyptian obelisk of Pharaoh Tutmose III. It was re-erected by Roman emperor Theodosius I in the fourth century AD in *Meydanı* or *Sultanahmet Meydanı*, the Hippodrome of Constantinople in Istanbul. The Obelisk silently explains the close link between early civilization and the study of birds, plants, and animals, from which ancient wisdom tirelessly tells stories of past glories.

Nature has nursed human culture and knitted unforgettable stories. At a school in ancient China, handsome Liang Shanbo met Zhu Yingtai. He thought Yingtai was a bright young fellow like him, and they became the best of friends. However, Yingtai was a beautiful girl disguised as a boy in order to attend the school, because girls were denied school education during that time. Eventually Shanbo realized Yingtai was a girl and wanted to marry her, but the Zhu family had already promised her to another family by matchmaking despite her unwillingness. Shanbo soon passed away due to extreme desperation. On the way to her marriage ceremony, Yingtai prayed at the grave of Shanbo, and the tomb magically cracked open. Yingtai jumped in, and suddenly, a pair of colorful butterflies flew out into the blue sky to continue their never-dying love story.

Wright Brothers National Memorial, Kill Devil Hills, North Carolina, the world's first controlled powered flight. Courtesy of US Department of the Interior, National Park Service

Nature-inspired technological development dates back to the days of the domestication of plants, grass, insects, birds and animals in order for people to have food and basic living supplies. Food production demanded continuous improvement of tools; travel and the exchange of goods required the innovation of faster and faster vehicles; the desire for victory in wars here and there necessitated high-speed missiles and long-distance information communication, just to name a few. Nature ignites people's imagination and spurs the invention of machines and systems that have never existed to meet these needs. Airplanes, submarines, and trains, as well as countless technological innovations like these, emerge from the images of their natural counterparts.

People dreamed of flying like a bird; some even sacrificed their lives when jumping into the wind with a pair of wings. It was not until the Wright brothers demonstrated the world's first controlled powered flight in 1903 in Kill Devil Hills, North Carolina, USA, that the aviation age was effectively launched. From then on, airplanes and spacecrafts have brought people's dreams to record-breaking heights.

Every object, natural or man-made, has its interior material structure and surface, and many biological and physical functions are accomplished through surfaces. The surface of one material system forms an interface with that of another, such as the interface between water and its container, pen and paper, shoes and the ground, blood and the blood vessel, meshing gear teeth, the tire and road, everywhere and every system where components are in contact and relative motion. In many cases, surfaces and interfaces determine system life, efficiency, functionality, reliability, and security. For example, frozen rain can result in heavy ice shells on power-line surfaces, leading to power transmission system damage. A typical ice-rain storm in Northeast United States may result in damages of about $4–6 billion dollars. Surface fouling can retard productivity in agriculture and cause inefficiency of ship navigation. Friction at interfaces and wear of surfaces result in energy waste and equipment damage. The significance of understanding surfaces can never be overestimated.

Nature has inspired the creation of countless products by means of mimicking natural systems; it is also unfolding its secrets of surfaces and stimulating future surface-based technologies to help people win the challenges of energy crises, environmental issues, and system reliability problems. Many are waiting to be done.

ME 346, Introduction to Tribology, is a course teaching the phenomena, theories, and principles related to surfaces and their interactions at Northwestern University, Evanston, Illinois, USA. Tribology is the science of interaction of surfaces in contact and relative motion, where understanding the science of surfaces is one of its major objectives. It is open to both juniors and seniors and graduate students. Twenty-three students enrolled in this class in the fall quarter of 2012. While teaching principles of tribology, such as contact, lubrication, friction and wear, I encouraged students to look around and see what nature tells us about surfaces and how people are developing novel technologies based on the understanding gained from the studies of natural surfaces. Nearly one half of the class was involved in learning the inspiration that natural surfaces could offer as the subject of their class projects. The class projects of these students resulted in 13 interesting articles, ranging from plants to animals and insects. The modification of these articles led to this book,

What micro and nano mysteries are behind the beauty of Jiu Zhai Gou Valley, China?

edited by Ms. Michelle Lee, one of the 346 students. Five students participated in the work, and others allowed Michelle to re-write the articles based on their original project reports. After ME 346, Michelle spent about 10 months of her free time to organize issues related to the book, write her own chapters, edit articles from other students, and communicate with the publisher. This book could not have been done without her effort. It is worth mentioning that Ms. Caroline E. Hartel, another ME 346 student, assisted Michelle in developing the proposal of this book's writing.

As presented in this book, lotus leaves, rice leaves, gecko pads, butterflies, diatoms, etc., have the microscopic wonders behind their pretty appearances. Many more astonishing surfaces of plants, algae, bacteria, animals, insects, stones, etc., are out there waiting for young students to explore, study, and dream up inventions from. Enjoy reading and thinking!

Evanston, IL, USA Q. Jane Wang, Ph.D.

Preface

There is an epidemic that has swept the entire nation—one that most are oblivious to. It is the epidemic of overly fast-paced, technology driven lives. Now, more than ever, Americans lead lives of busyness and constantly being on the run, with cell phones, email, and tablets at the ready.

At some point we have to wonder… Could we be eliminating something valuable from our lives with this kind of lifestyle? But, of course, just as soon as these thoughts form in our heads, they disappear at once as the phone chirps, and we grab it to see who texted us.

The truth is that there *are* many valuable things we ignore every day. In fact, there are a thousand, a billion, an *infinite* amount of things, perhaps right outside our windows or in the ponds near our houses. They may even be found amidst the mass of forest trees along the highway we took today on our commute to school or work, or in the park that we walked our dogs in. With such a rapid increase in the rate of technology usage, it is easy to forget nature, the master inventor.

But we always have the ability to stop, and truly look.

> When we stare this deeply into nature's eyes, it takes our breath away, and in a good way, it bursts our bubble. We realize that all our inventions have already appeared in nature in a more elegant form and at a lot less cost to the planet. Our most clever architectural struts and beams are already featured in lily pads and bamboo stems. Our central heating and air-conditioning are bested by the termite tower's steady 86 degrees F. Our most stealthy radar is hard of hearing compared to the bat's multifrequency transmission. And our new 'smart materials' can't hold a candle to the dolphin's skin or the butterfly's proboscis. Even the wheel, which we always took to be a uniquely human creation, has been found in the tiny rotary motor that propels the flagellum of the world's most ancient bacteria.
>
> –Janine M. Benyus, *Biomimicry: Innovation Inspired by Nature*

Nature is a bountiful source of inspiration and intelligence, and many have been using it for scientific exploration for ages. Such examples include gecko pads, lotus leaves, butterfly wings, sharks, and more. This book presents 13 different kinds of natural surfaces—many of which we can easily find near our houses—and their respective science and engineering values. The chapters in this book were written by students in Professor Q. Jane Wang's Introduction to Tribology class taught at Northwestern University in Evanston, IL. USA. All passionate about nature, the contributing student authors strive to share their understanding with the communities around them.

After reading the fascinating examples of natural surfaces in the following pages, may you be inspired to slow down, get some fresh air, and discover for yourself all that nature has to offer.

Evanston, IL Michelle Lee

Acknowledgements

I would like to thank Professor Q. Jane Wang for her mentorship from beginning to end, as well as her inspiring teaching throughout the Introduction to Tribology course at Northwestern University.

I would also like to take this opportunity to express sincere gratitude to the participants of this book:

Mindie Chu, Ignacio Estrada, Shiqi Luohong, and Yunho Yang, for their hard work and contribution that made this book possible;

Caroline Hartel, for her enthusiasm and her help with getting this book off the ground, as well as allowing me to use her draft as a basis for the chapter on lotus leaves;

And Elizabeth Bifano, Rose Gruenhagen, Joseph Park, and Christopher Timpone, for allowing me to consult their drafts in writing the chapters on gecko pads, spider silk, snake skin, and dragonfly wings, respectively.

Contents

1 Blood Clots and Vascular Networks: Self-Healing Materials

Michelle Lee

The Gift of Regeneration and Renewal

Though many childhood memories fade over the years, there are some that remain vivid as we enter into adulthood. Though these memories may range from bitter to sweet and differ per person, most can recall that *one* accident, be it falling off the bike and getting scraped from head to toe by the pavement, breaking or fracturing a limb during a rowdy game of street hockey with some neighbors, or getting a huge cut doing something just plain dumb. This is most likely the story that gets shared at every family reunion or as an interesting personal anecdote. Whatever the story, talking about it in adulthood is usually painless—often even humorous and sweet. We are able to share our stories nostalgically, because what is left of the accident is a mere scar—many times not even that. This is a direct result of our bodies' phenomenal self-healing and renewing capabilities.

On the other hand, unlike us, most of the objects we use on a day-to-day basis are on a one-way road to deterioration. In other words, the scratch we made on our car the other day from a bad parking job will be there in a year, along with all the other dents and scratches we make in between. The web-like crack in our window from the neighbor's rogue baseball will be there to obstruct the nice view of our backyard for weeks to come until we replace it. Objects must be replaced, and replaced, and replaced.

Engineers hope that one day, this will not be the case for certain applications in which self-repairing ability would be particularly advantageous. This area of research is called self-healing materials, and the following sections will give an overview of the bio-inspiration behind self-healing materials as well as current and future applications.

M. Lee (✉)
Mechanical Engineering, McCormick School of Engineering
at Northwestern University, Evanston, IL 60208, USA
e-mail: MichelleLee2013@u.northwestern.edu

M. Lee (ed.), *Remarkable Natural Material Surfaces and Their Engineering Potential*,
DOI 10.1007/978-3-319-03125-5_1,

Self-Healing Materials

What Does It Mean to Be Self-Healing?

A material is self-healing if it can recover from damage without external intervention. Other words that have been used interchangeably with self-healing include autonomic-healing, autonomic-repairing, and self-repairing (Ghosh 2009). Perhaps one of the biggest differences between most living organisms and engineered materials is the ability to adapt and heal in response to damage and degradation. Engineered materials generally lack the inherent ability to fix themselves, and they deteriorate over time due to degradation, whether it is in the form of fatigue, creep, brittle fracture, wear, and so on. This deterioration is irreversible, leading many materials to catastrophic failure (Nosonovsky 2012).

Current Engineered Materials

According to van der Zwaag et al., engineered materials' inability to self-heal is a result of its underlying *damage prevention* paradigm, as opposed to nature's underlying *damage management* paradigm. The *damage prevention* paradigm, which dominates the development of all engineering materials, is defined by a design strategy of most effectively delaying the onset of deterioration and damage. As a result, today's engineering materials will only experience an increase in damage or, in the best case, remain at a constant level.

On the other hand, nature's inherent *damage management* paradigm allows damage to be unproblematic, since the damage can be self-healed (van der Zwaag et al. 2009). The lack of autonomous self-healing mechanisms in engineering materials necessitates human intervention and efforts to remedy effects of deterioration, which most often take the form of welding, resin injection, and applying reinforcement patches. These methods are typically imperfect and leave the repair site as the weakest point. Therefore, materials that can self-heal at the micro- and even nanoscale level are of great interest to scientific communities (Guimard et al. 2012).

Advantages of Self-Healing Capabilities

Healing mechanisms of living organisms are extremely complex, making it difficult to mimic them. In addition, copying the healing mechanisms of nature is unwise, because the intrinsic character of engineering materials has to be taken into account when designing self-healing materials (van der Zwaag et al. 2009). However, nature is a source of bio-inspiration for researchers who are seeking to create self-healing materials for the future of engineering (Nosonovsky 2012). Such self-healing materials are "smart" materials: materials designed to have a predetermined and controlled response to a particular stimulus. Theoretically, using self-healing materials would fail less often, have a longer lifetime, and decrease the frequency of maintenance as well as the costs associated with such tasks (Guimard et al. 2012). Furthermore, self-healing materials would ensure repair of damages that occur in remote or hidden locations (Ghosh 2009).

'Bleeding' Approach to Self-Healing

Blood Clotting as Bioinspiration

A simple observation of nature is that animals self-heal by means of a 'bleeding' mechanism (Trask et al. 2007). In humans, this is often encountered at a young age at the first cut or wound. From then on, bleeding simply becomes a part of life, the unavoidable and rather unpleasant intermediate step between getting hurt and healing. However, bleeding leads to blood clotting, a process critical to the body's healing ability, which involves interactions between the damaged tissue, blood plasma, and blood platelets. Blood clotting was observed with much fascination by early scientists and philosophers who marveled at the body's natural ability to heal wounds through the clotting mechanism. Galen (129–199 AD) was one of them, describing threads that he observed in blood clotting. Malpighi also noticed threads and nerve-like networks in 1666 (Ferguson et al. 2010).

Today, we know much more about the details of mammalian blood clotting. The threads that were observed and marveled at by Galen and then Malpighi are known as fibrin fibers, which are composed of protein and produced when a wound breaches the endothelial cell lining of blood vessels. This breach initiates a sort of cascading series of active enzymatic reactions that involve inactive precursors called clotting factors, ultimately resulting in fibrin (see Fig. 1.1). Blood clotting is remarkable in that it rarely malfunctions. In fact, the body continues to take measures to prevent further damage, rapidly removing activated enzymes once fibrin is produced and avoiding clots in healthy blood vessels by breaking fibrin down in any undamaged areas. Overall, the blood clotting process involves around 80 coupled biochemical reactions of platelet cells and enzymes (Trask et al. 2007). Clotting is thought to be a self-regulating procedure, and this self-regulation is elemental to the success of its two basic features. One feature is its threshold response; clotting will only occur in a blood vessel that is substantially damaged. The other feature is its locality, occurring only in a confined region in the immediate vicinity of the damage (Runyon et al. 2004).

Despite the wealth of knowledge about the specific mechanisms involved in blood clotting that had not been available in Galen and Malpighi's time, the fascination with the process still continues today, as blood clotting has become a source of bioinspiration for the development of self-healing materials. Using blood clotting as a biomimetic platform would be difficult considering the number of reactions involved and its complexity (Runyon et al. 2004), as evident in the previous section. However, it has inspired the use of liquid healing agents that leak from fractured openings of damaged hollow fibers or capsules as a form of autonomic self-healing (Trask et al. 2007).