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Foreword

The word "tribology" was introduced in 1966 to embrace the separate subjects of friction, wear, lubrication, and bearing design. Most machinery involves interacting surfaces in relative motion, and a sound understanding of the fundamental nature of these interactions is essential for future progress.

Human bodies illustrate many fine examples of tribology, from load-bearing synovial joints to teeth and the oral environment. Interest in these examples of biological and medical tribology precipitated the introduction of the term "biotribology" in 1973. The latter, fascinating field has represented one of the most active areas in tribology research in the past half-century.

Recent interest in biotribology is evident in the vast growth in published journal papers, chapters in tribology books, and sessions carrying the title in international conferences. The present text by Professor Zhong-Rong Zhou and his colleagues in China, devoted entirely to teeth, is a natural and welcome extension of these rapid and important developments.

The authors emphasise the multidisciplinary nature of their subject, which embraces dental and medical concepts and well-defined aspects of tribology. Terminology has long been a problem. For example, the word *attrition* is widely used and understood in dentistry, yet in tribology it is the five distinct forms of wear defined as abrasion, adhesion, corrosion, erosion, and fatigue that are adopted and investigated. *Erosion* is defined differently in the dental and tribological fields, and the differences between *erosion* and *corrosion* are rarely recognised in dentistry. These examples immediately draw attention to one of the difficulties in this multidisciplinary field, which relies upon contributions from engineering, physics, chemistry, materials science, biology, dentistry, and medicine.

The authors remind us that concern for dental health has a long history. Tooth-cleaning procedures developed over thousands of years, while dental implants have been used for over a thousand years. Attempts to link age to tooth wear have been of interest for many years in medical, dental, and forensic fields.

The interesting structure of the hardest organs in the body is outlined and the basic mechanical properties of the natural materials quantified, while those for restorations and fillings are also introduced. These well-illustrated features of teeth will be of particular interest to tribologists and material scientists. While fracture of enamel and dentin inevitably calls for the introduction of alternative materials, the evaluation of wear is difficult. In vivo estimates necessarily extend over long periods of time, and difficulties arise in the measurements over relocation. Laboratory methods, based upon many familiar tribological test procedures, have to be undertaken in meaningful environmental conditions and under realistic dynamic loads and speeds.

An impressive range of reciprocating friction and wear tests between a titanium alloy ball and specimens of teeth in artificial saliva are reported for subjects of various ages. The role of microstructure in friction and wear processes is clearly evident. Tests were carried out at different depths of wear through the enamel and beyond the enamel-dentin interface. Initially, the coefficients of friction were about 0.1, but as penetration increased, the values rose to about 0.85. Surface analysis instruments revealed the microstructure and wear interface, with the enamel rods being clearly evident.

An in-depth account of the role of environment upon friction and wear demonstrates in impressive style the severity of acidic environments associated with soft drinks, fruit juices, and sports drinks. The value of micro-and nano-hardness tests in tribological studies of enamel is well illustrated. The current range of restorative materials is presented and comparisons made with natural materials such as dentin and enamel. Ideally, restorative materials should exhibit similar wear to normal enamel under the wide range of loading conditions, motion, temperature, and environment encountered in the mouth, but this goal has yet to be fully achieved. Current restorative materials include metals and their alloys, composites, and porcelains.

Human teeth are subjected to many very small movements in normal functioning in the mouth, and the phenomenon of fretting, particularly at the implant-interface, attracts particular attention. While fretting cannot be avoided during mastication, greater understanding of its nature and extent could benefit the drive towards reliable osseointegration.

Many factors contribute to dental caries, and the authors discuss the role of diet, sealants and restoratives, remineralization and demineralization, fluoride, amorphous calcium phosphate, Galla Chinensis, hydroxyapatite, and laser irradiation. Biomechanical, tribological, physiological, and pathological factors in the process are also discussed, once again emphasising the need to integrate many separate disciplines in further studies.

The authors are complimented on bringing together accounts of dental, tribological, and materials science studies of natural teeth, together with their assessments of the performance of revision and replacement materials. The considerable number of experiments already undertaken is recognized, but it is noted that the field would benefit from a systematic approach to research. This is one of several fields in biotribology which would certainly benefit from more holistic approaches. It represents a challenging task, but the present text will do much to further promote collaborative research and benefit patients.

Leeds, UK Duncan Dowson

Preface

I turned my attention to dental friction and wear when I chatted with a dentist in 1998. In fact, human teeth are the masticatory organ and therefore subjected to friction and wear functionally every day under a complex oral environment and loading condition. What makes human teeth adequate to serve for a lifetime in the mouth with complex physical and chemical processes has been a puzzle, which initially motivated us to get through the work presented in this book focusing on dental wear. Dental wear is one of the most important parts of and also on the leading edge of biotribology, However, the benefit of its achievements is far beyond the recent studies. The accumulation of the scientific knowledge about human teeth can provide invaluable insights into the developments of advanced dental materials, oral practices, archaeology and also stimulate the bionic design by transferring the antiwear properties of human teeth into engineering antiwear systems. I believe in next decades that more researchers will be involved and will usher in significant progress in dental wear research.

The present book is a research snapshot of my group in the last a few decades together with a summary of the literature. I am grateful to the contribution to the work from my postdoctorate, Dr. Hong Li. Additionally, I would like to express my appreciation for the valuable help from some graduate students: Dan Yang, Mao-Yu Shi, Ming Wen, and Shan-Shan Gao, in collecting documents and preparing the figures. In addition, this book is deeply indebted to the National Natural Science Foundation of China for its financial aid.

I hope that the information presented in the book will be of interest to clinical dentists, engineering tribologists, and materials researchers. I also hope that readers of this book may, if they are not doing so already, be stimulated to work in this fascinating field.

Chengdu, People's Republic of China　　　　Zhong-Rong Zhou

Contents

Chapter 1
Introduction to Teeth

Human teeth are not only an important masticatory organ but also closely associated with both the pronunciation and facial aesthetics of humans. Without a doubt, teeth play an extremely significant role in our daily life. The wear of teeth, either natural or artificial, is unavoidable. However, excessive wear may lead to a lack of perfect contact between opposite teeth, a disturbance in the efficiency of the masticatory system, and an obliteration of chewing surfaces. Teeth also play a very important role in animals' lives. Historically, the wear of teeth has been considered an indicator of age for animals.

The application of tribology in dentistry is a growing and rapidly expanding field. Intensive research has been conducted to develop an understanding of dental tribology for the purposes of a better selection of artificial dental materials and the design of implant teeth. Dental wear, or dental biotribology, has been one of the most important branches in biotribology in recent years.

1.1 Biotribology

Although wear, friction, and lubrication have been studied for many years, the term "tribology" was first introduced in 1966 in the Jost Report and was defined as "the science and technology of interacting surfaces in relative motion and the practices related thereto." In brief, tribology deals with lubrication, friction, and wear, which include a number of basic disciplines such as mechanics, material science, chemistry, and physics, among others. For decades, industrial problems have been responsible for the recognition of the concept of, and the word, "tribology." Typical engineering components such as ball bearings, gears, and wheels have been widely investigated. However, it soon became obvious that an understanding of the nature of the interaction a between loaded and moving surfaces would be equally important in studies of biological systems. The word "biotribology" was first used in 1970

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and defined by Dowson and Wright in 1973 as "those aspects of tribology concerned with biological systems" [1].

Biotribology is currently one of the most exciting and rapidly growing areas of tribology. The range of research activities is immense and spans many scientific fields. A considerable number of papers on biotribology have been published in various journals. In addition, many sessions of conferences, national or international forums, workshops, and symposia have been held on biotribology or on topics related to it. For example, in 1967, the symposium on Lubrication and Wear in Living and Artificial Human Joints was organized and held in London by the Institution of Mechanical Engineers in collaboration with the British Orthopaedic Association; it attracted over 160 delegates. In 1996, a report of a workshop organized by Lloyd et al. was published. Eighty delegates contributed to a valuable discussion; the purpose was to bring together tribologists, clinicians, and dental materials scientists to discuss the fundamental mechanisms of wear and how to obtain manifestations and conduct measurements of wear in dentistry [2]. Subsequently, the First Vienna Symposium on Biomechanical Engineering was organized during the 2nd World Congress on Tribology in 2001. The Symposium on Human-related Tribology during the 4th World Congress on Tribology in 2009 and the 6th International Biotribology Forum in 2011 were also held [3–6]. However, the meeting with the largest scale was the 2011 International Conference on Biotribology held at Imperial College, London [7]. To the surprise of the Organizing Committee, 175 abstracts for oral and poster presentations on various subjects were received, such as artificial hip joints, skin and haptics, personal care products, articular cartilage, human teeth, lifestyle and home healthcare devices, artificial heart valves, bones, hair, and eyes, and about 300 delegates from over 20 countries participated in the conference, which shows the growth and diversity of the research area of biotribology. Evidently, there have been many more scientific sessions on the topic of biotribology in various conferences and meetings. This shows that biotribology has been one of the most studied and active research areas in the field of tribology.

1.2 Classifications and Definitions

According to the Organization for Economic Cooperation and Development's (OECD) Glossary of Terms and Definitions in the field of friction, wear, and lubrication (tribology), wear is defined as http://stats.oecd.org/glossary/ "the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface." In the field of tribology, five wear mechanisms rather than wear modes have been frequently recognized: abrasion, adhesion, fatigue, erosion, and corrosion. In most cases, two or more wear mechanisms combine together and contribute to the material degradation processes.

Wear by abrasion is associated with the displacement of material from a relatively soft solid by the protuberances on a harder counterface, or by loose, harder

Table 1.1 Classifications and definitions of tooth surface loss

Mode	Definition
Abrasion	The pathological wearing away of dental hard tissue through an abnormal mechanical process involving foreign objects or substance repeatedly introduced in the mouth and contacting the teeth
Attrition	The physiological wearing away of dental hard tissue as a result of tooth-to-tooth contact with no foreign substance intervening
Erosion	The physical result of a pathologic, chronic, localized, painless loss of dental hard tissue chemically etched away from the tooth surface by acid and/or chelation without bacterial involvement
Resorption	The process of biological degradation and assimilation of substances or structures previously produced by the body
Abfraction	A special form of wedge-shape defect at the cementoenamel junction of a tooth
Demastication	The wearing away of tooth substance during the mastication of food with the bolus intervening between opposing teeth

Source: From Imfeld [11]

particles between two surfaces. *Adhesive wear* is the process by which material is transferred from one surface to another during relative motion. *Fatigue wear* is frequently related to the formation of surface or subsurface cracks, and then particles of detachment under repeated and higher contact stress condition. *Wear by erosion* mainly describes surface damage in either a liquid–solid or gas–solid flow system. *Corrosive wear* is considered substance loss under chemical or electrochemical action often combined with relative motion. Fine debris detached from the surface and fresh contact surface exposed to be oxidized are typical forms of corrosive wear.

With the help of an Internet search engine (http://scholar.google.com) in July 2012, on the keywords "teeth and wear," more than 400,000 pieces of information are recorded mainly in the archaeological and medical literature, extending over many centuries. Dental wear is considered a tribological problem. However, major research papers that have been published in various medical journals related to dental research, dental material, oral rehabilitation, and the like focus on the consequences of dental wear but not on the mechanisms of dental wear [8–10]. This book will illustrate why researchers and dental scientists need a deepened understanding of the behaviors of dental wear.

In the dental literature, there are many different classifications and definitions to describe tooth surface loss, including surface wear [9, 10]. A representative overview on tooth wear was made by Imfeld [11]; six kinds of noncarious tooth loss, including abrasion, attrition, erosion, abfraction, resorption, as well as demastication, were identified, as listed in Table 1.1.

In most cases, the terms "dental abrasion," "attrition," "erosion," and "abfraction" have been frequently used in the field of dental research. However, it should be noted that the definition and classification of tooth surface lesions have been in a state of confusion when used in tribology terminology. For example, there is no such term "attrition" in the research of general wear for tribologists. In fact, "attrition" merely indicates a two-body contact, such as tooth to tooth or tooth to denture contact by mastication, and it is not considered to cause any damage. However, based on tribological terms, “attrition” would be clearly subsumed under other well-defined surface damage mechanisms. Moreover, there is a huge difference in the definitions of the term “erosion.” It seems that the meaning of “erosion” used in tooth loss is similar to that of “corrosion” used in tribology. In 2004, Grippo et al. [12] also proposed that the term “erosion” should be deleted from the dental lexicon and replaced with the term “corrosion” to denote chemical dissolution of teeth. In addition, “abfraction” is more or less related to higher bite force or repeated contact load, pointing to a relationship with the effect of fatigue. It might potentiate tooth wear by abrasion and/or erosion. On the contrary, the term “adhesion,” which is widely used in the field of tribology, is not encountered in the dental literature. The explanation might be that dental tissue, particularly dental enamel, is similar to ceramic materials; perhaps adhesive wear would not occur at the tooth surface during the masticatory process. Nevertheless, respecting disciplinal differences and development history, these terms will still be used although engineers and medical researchers should use care when reading these terms in the literature.

1.3 Anatomy and Function of Human Teeth

Human teeth possess a unique structure [13] composed of enamel, the dentin–enamel junction, dentin, and pulp (shown in Fig. 1.1); each zone is anisotropic. The two most important elements of a tooth from a tribological perspective are the outer enamel and the inner dentin, whose properties [14] are given in Table 1.2.

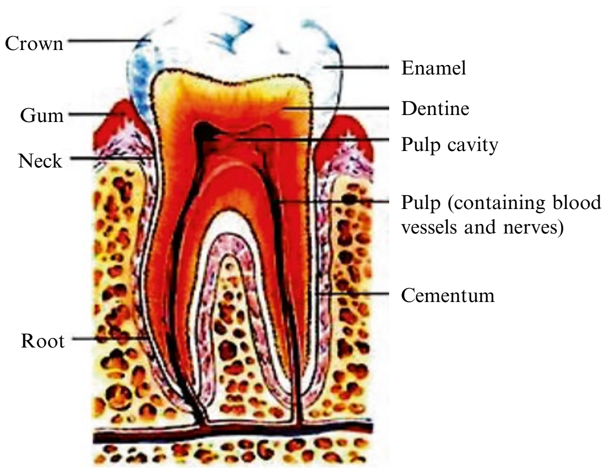

Fig. 1.1 Human tooth structure [13]

Table 1.2 Mechanical properties of enamel and dentin

Property	Dentin	Enamel
Young's modulus (GPa)	10.2–15.6	20.0–84.2
Shear modulus (GPa)	6.4–9.7	29
Bulk modulus (GPa)	3.11–4.38	45.65
Poisson's ratio	−0.11–0.07	0.23, 0.30
Compressive strength (GPa)	0.249–0.315	0.095–0.386
Tensile strength (GPa)	0.040–0.276	0.030–0.035
Shear strength (GPa)	0.012–0.138	0.06
Knoop hardness	57–71	250–500
Density (kg/m^3)	2,900	2,500

Source: From Braden [14]

Enamel is the hardest tissue in the human body, while dentin is usually considered to be elastic and soft. Initially, the enamel, which has a thickness of 2–3 mm, is exposed to the occlusal surface and chemical environment within the mouth. Enamel is composed of 92–96 % inorganic substances, 1–2 % organic materials, and 3–4 % water by weight [15]. Most of the inorganic substances are hydroxyapatite, which is contained in the basic structural unit of enamel, the rod or prism. These prisms align and run approximately perpendicular from the dentin–enamel junction toward the tooth surface [16–18]. The high hardness of enamel is attributed to its high mineral content, while its brittleness is due to its high elastic modulus and low tensile strength. Investigations have shown that the mechanical properties of enamel vary with locations on a tooth, local chemistry, and prism orientation [18–20]. Finite element stress analysis results showed that the enamel absorbs most of the applied chewing load during mastication due to its greater stiffness as compared to dentin; therefore, masticatory forces tend to flow around the enamel cap to the root dentin [21].

Dentin is a hydrated biological composite composed of 70 % inorganic material, 18 % organic matrix, and 12 % water by weight, and its properties and structural components vary with locations [22]. The structural composition of dentin includes oriented tubules surrounded by a highly mineralized cuff of peritubular dentin and an intertubular matrix consisting of type I collagen fibrils reinforced with apatite. Between enamel and dentin, the dentin–enamel junction, a biological interface, may dissipate stresses, inhibiting further crack propagation [23, 24]. The dentin–enamel junction has a high fracture toughness and, along with the more resilient underlying dentin, supports the integrity of enamel by preventing its fracture during function. Another possible mechanical function of the soft dentin beneath the dentin–enamel junction may be related to the ability of a whole tooth to resist impact forces, which often occur when the tooth is working [25].

The major functions of teeth, together with any restorations and implants, are associated with speech, breathing, tasting, and chewing, and with supporting bone, soft tissues, and the muscles of mastication. Initially, a human has 20 primary (or baby) teeth [26]. These are eventually replaced, during childhood, with 32 permanent (or adult) teeth. To allow chewing, teeth are arranged into two opposing arches in the mouth. Within each arch are different types of teeth (Fig. 1.2), each of