Green Tribology

Green Tribology:

Principles and Practice

By

Siwei Zhang

Cambridge
Scholars
Publishing

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This book first published 2025

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

ISBN: 978-1-0364-4727-4
ISBN (Ebook): 978-1-0364-4728-1

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FOREWORD

Within the enormous size and scale of the universe, our small and solitary planet, Earth, is the only known place where life has existed in very diverse and different forms. It has been a home for humans and many other living species for millions of years. With the start of the Industrial Revolution energized by coal, the amount of carbon dioxide (CO2) in the air started to creep up from its reasonably steady state of about 300 ppm to well above the 400 ppm levels of today. With increasing population, mobility, and industrial activity, CO2 levels in our atmosphere will undoubtedly continue to increase in the coming years, especially if we do not act very quickly. Such a trajectory will further exacerbate global warming and, hence, climate change that can have a devastating impact on our delicate ecosystem. The biggest dilemma before us is reversing this unsustainable trend and hopefully saving our planet from a major climate catastrophe. Alarmed by these circumstances, world leaders have collectively agreed, for the very first time, to do all they can to significantly reduce CO2 emissions with the aim of limiting the global mean temperature increase to below 2°C, with an even more ambitious goal of limiting it to 1.5°C above pre-industrial levels by cutting greenhouse gas (GHG) emissions by half within this decade, with even deeper cuts in the following decades. Overall, these UN-sponsored climate conferences have been very useful in that most world leaders now recognize the adverse impacts of GHG emissions on climate change and are taking major steps to fix it.

How can tribology or green tribology contribute to reducing GHG emissions and save our planet from an irreversible climate catastrophe? From the results of UN climate summits, it has become clear that we must transition to renewable energy sources such as wind and solar very quickly while increasing the efficiency of all energy conversion and utilization systems and removing or capturing the CO2 from our atmosphere and storing it safely. In particular, we must develop and embrace emission-free vehicles, such as electric vehicles powered by batteries instead of internal combustion engines. At the same time, we must also enhance the efficiency and reliability of traditional vehicles so that they consume far less energy and emit much lower GHGs.

Green tribology, which advocates using clean energy sources and environmentally friendly industrial practices, has been an important area of tribology mainly because it encourages energy conservation, ecological balance, recycling, and environmental protection, all of which support sustainability goals. The author of this book, Professor Siwei Zhang, was undoubtedly one of the earliest pioneers of the concept of green tribology. As early as 2001, he introduced this concept in China but it was not until 2008 that he more passionately and eloquently laid out what it meant in a plenary lecture at the 5th China International Symposium on Tribology. Since then, the concept started gaining more traction and attention from the visionaries of our tribology field, including a strong endorsement by the late Professor Peter Jost, the founder of modern-day tribology and the first President of the International Tribology Council. Professor Jost arranged a visit for Professor Siwei Zhang and Professor Jianbin Luo in the UK. Following their visit, the green tribology concept was featured in many opening addresses of major tribology conferences, including the Fourth World Tribology Congress in Kyoto, Japan.

These concerted efforts have culminated in the publication of some reports and review articles that helped promote green tribology as a new branch of tribology, however, they were far from providing the whole picture. As can be imagined, an exact understanding of its fundamentals is essential for the further development and expansion of the field of green tribology. In this respect, the Green Tribology book by Professor Siwei Zhang is very timely. It aims to fill such gaps by providing a more concise and comprehensive explanation of the principles of green tribology, including its fundamentals, key characteristics, and societal impacts. Therefore, this book's publication has an important practical significance and a profound societal implication for a clean, green, and sustainable planet for generations to come.

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PREFACE

As early as 2001, in response to the global shortage of resources and energy, as well as the increasingly deteriorating ecological environment, the present author first proposed the new concept of "green tribology" in China, but it did not attract attention for a long time. In 2008, when he once again advanced this concept in his plenary lecture at the 5th China International Symposium on Tribology, it was immediately aroused the attention of Prof. Jost, the founder of tribology and the first session President of International Tribology Council.

In June of the following year, Jost actively planned and facilitated a visit of the Chinese Tribology Institution delegation led by the present author and Professor Jianbin Luo to the United Kingdom. He recommended that the theme of the visit be "green tribology", and expected that this visit could promote the development of green tribology in the UK (see Appendix).

Three months later, Jost earnestly pushed forward the new area "green tribology" to the international tribological community in his opening address with the theme of "Green tribology-A footprint where economies and environment meet" at the Fourth World Tribology Congress at Kyoto in Japan. Later on, a batch of papers was published. Since then, under his long-term and unremitting advocacy, green tribology was received increasingly widespread international attention, and spread rapidly as a new branch of tribology.

However, in recent years, the term "green tribology" was rarely appeared and almost disappeared in the international tribology community. The occurrence of this situation is not accidental. In fact, as early as 2010, the present author was a little surprised for that some scholars were so quickly published papers involved various aspects under the title of green tribology. They accepted this new term "green tribology", could be based on their own research fields and understood the concept of green tribology only from a certain aspect.

In addition, perhaps some scholars view green tribology as a loose combination of various related or seemingly related disciplines and research fields.

To this end, the present author worried about that the future development of this new field could be misled, and expressed to Jost: “In order to avoid this situation, it is required of further work in a down-to-earth manner … Investigating the fundamentals of green tribology. Otherwise, green tribology would be a flash in the pan” (personal communication, Nov. 30, 2010). Jost replied: “I am at present preparing an Overview of Tribology and Green Tribology as a first step to tell the uninitiated what Tribology and Green Tribology is about. I certainly agree with your suggestion for an extended version” (Dec. 9, 2010). Later on, the present author also issued an article to clarify the fundamental basics and the main contents of green tribology [Green tribology: Fundamentals and future development, Friction, 1(2), 2013].

Green tribology as a new branch of tribology is still in the infancy. Up to now, very few research topics were touched upon its elemental basics, and also not a single work to discuss its principle in precise terms and in an all-round way. However, the exact understanding of its fundamentals is the present author’ scientific basis for further development of green tribology. Therefore, there is a lack of research and rational understanding of the principles and practices of green tribology, as well as its future development, which has led some tribologists to feel confused about its future prospects. This is precisely the main reason why this new discipline has been neglected in recent years.

Connected with this, the present author believes that it is necessary to publish a monograph to elucidate comprehensively and systematically the basic principles and practical contents of green tribology.

In addition to long-term important tasks such as energy conservation, emission reduction, and improving human quality of life/existence, green tribology will also face with some unprecedented tribological problems related to global challenges in the future, including natural disasters and shortages of food and drinking water. Obviously, while faced with these severe challenges, green tribology will inevitably gain broader development opportunities. Green tribology has a long and promising future. Therefore, the publication of this book not only has important practical significance, but also has profound significance.

The aim of this current work is intended to clarify the fundamental basics, technological connotations and the perspective of green tribology based on the analysis, synthesis, and summary of the research achievements in the development of green tribology over the past decade, which also includes the theoretical research findings related of the present author.

The entire book consists of nine chapters and an appendix. Chapter 1 introduces the emergence background and the scope of green tribology; Chapter 2 clarifies the basic concepts and principles of green tribology; Chapters 3 and 4 are the basic practical contents of green tribology; and Chapters 5-7 introduce three special contents of green tribology separately. In Chapter 5, the new term "natural disaster tribology" and its basic concepts are advanced, having first been done so at the beginning of 2022; Chapter 8 overviews the application of biomimetic surface technology/engineering in the oil and gas industry. This chapter is mainly taken from the article: Yanbao Gao, Zheng Zhang, Siwei Zhang, Advances in the application of biomimetic surface engineering in the oil and gas industry, Friction, 7(4): 289-306, 2019. The contents of this chapter are closely related to green tribology. The last chapter looks forward to the development prospects of green tribology.

During the writing process, this book received strong support from Professor Luquan Ren of Jilin University, Professor Xinping Yan and Professor Xiuqin Bai of Wuhan University of Technology, and Professor Guangxiong Chen of Southwest Jiaotong University. They provided high-level scientific papers (including charts) for reference and citation. The present author hereby expresses his heartfelt gratitude to them. In addition, Professor Yanbao Guo of China University of Petroleum at Beijing assisted in collecting literatures and creating charts; Ms. Zhang Rui, Senior Engineer, completed the text editing of the entire book. Here, the present author would like to express his gratitude together.

About the Author

Siwei ZHANG is the professor of Tribology and Mechanical Engineering of the China University of Petroleum in Beijing. He is the honorary director of the Chinese Society of Mechanical Engineering and the deputy director of the steering committee of the State Key Laboratory of Solid Lubrication of the Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences. He as formerly served as the Chairman of the Chinese Tribology Institution (CTI) and the Chairman of the Advisory Committee of the CTI in succession.

From 1982 to 1984, as a visiting professor, he studied in tribology of polymers at the Institute of Polymer Science, University of Akron, and then at the Tribology Laboratory, Department of Mechanical Engineering and Applied Mechanics, University of Michigan in USA. In 1987, he conducted researches in elastomer tribology at the Particle Technology and Interfacial Phenomena Group, Department of Chemical Engineering and Chemical technology, Imperial College of Science, Technology and Medicine in UK.

His professional interests mainly include tribology, surfacial mechanochemistry and oilfield equipment. He mostly conducted and supervised in tribology of polymers, friction materials, nano-tribology and tribological components. He has long term adhered to research in rubber tribology and published monographs "Wear of Elastomers" and "Tribology of Elastomers". At the beginning of this century, he first proposed the new term "Green Tribology" and advocated the development of this new branch of tribology that is related to promote sustainable development of nature and society.

In 2009, he received the Brilliant Contribution Award in Tribology of Chinese Tribology Institution.

CHAPTER 1

INTRODUCTION

1.1 Emergence of green tribology

Since the end of the last century, resource, energy and environmental crises on a global scale have become increasingly fraught. This situation has aroused great concern among tribologists, and some new tendencies have appeared in the international tribological circle.

In 1997, the 24th Leeds-Lyon Symposium of Tribology had the theme of "Tribology for energy conservation". The only plenary presentation was entitled "A role for tribology in life cycle design [1]", in which the life cycle thinking was introduced into tribology for the first time.

Life cycle thinking is an approach to assessing the environmental implications of a product. Life cycle design (LCD) might also be considered as the ecological design of product. Moreover, at this meeting, a famous scholar appealed the tribologists to develop the "greening" of materials technology in his talk [2].

Three years later, at the 27th Leeds-Lyon Symposium of Tribology in 2000, a new term "Environmental tribology" appeared. In that same year, at the Japan International Symposium on Tribology, a keynote speech related to life cycle assessment (LCA) was presented at the session titled "Environment aspect of tribology". LCA is considered as the "cradle-to-grave approach". It means that all the material and energy flows of a system or product are quantified and evaluated in its life cycle. Furthermore, a book titled "Tribology in Environmental Design 2000" was published in London at the same time [3]. Clearly, energy and the environment had become two challenges tribologists faced with.

At the beginning of 2001, the present author first advanced the term "green tribology", in the understanding that tribology should be developed unceasingly to address these challenges [4]. The word "green" shows a consciousness of the sustainable development of nature and society. Moreover, he expounded the concepts of green tribology (research objectives, tasks, aims and contents), and pointed out that its research objectives and technological connotations (research contents/areas) covered both tribology for energy conservation and environmental tribology/ ecological tribology [4].

During 2001 and 2002, the tribology group of the Committee of the Institution of Engineering and Technology in the UK organized a series of seminars to highlight the value of tribology and outline its development. The new term "Total tribology" was advanced. It was defined as "the practice of considering tribology at all stages of the life cycle of interface components" [5].

Since 2002, the International Conference on Tribology in Environment Design has been held at the University of Bournemouth in the UK each year. In 2004, the 31st Leeds-Lyon Symposium of Tribology was held at Leeds. The theme of this conference was "Life cycle tribology". The following year, the 3rd World Tribology Congress held at Washington DC focused on environmental protection, energy conservation and sustainable development.

The above indicates that energy and the environment had become the most important subjects of concern for tribologists. Moreover, the research subjects of tribology should be expanded unceasingly to suit the change and development of the nature and society. The basic subjects of tribology, originated it in 1966, were "controlling friction, reducing wear, and improving lubrication". The saving of energy and materials remain central concerns. In this respect, tribology is much better able to meet the demands of a sustainable society. However, it did not consider at first the ecological balance and environmental impact, owing to the limitations of the times.

In 2008, the concept of green tribology was raised again by the present author at the 5th China International Symposium on Tribology in a plenary lecture [6]. In this lecture, an investigation of the beneficial economic effects of the application of tribology in Chinese industries was introduced [7]. It was shown that a reasonable estimate of savings through tribology was 414.8 billion USD per year, equivalent to 1.55% of China's GNP in 2006.

The results seem to be concerned only with the economic benefits derived from the application of tribology. However, these benefits were acquired from reducing the consumption of both energy and materials, which implies a reduction in carbon dioxide emission and harmful particle discharge. Based on this investigation, the present author pointed out that "making the tribology green" could be one of the key directions of the technological progress of tribology in the new century, and held that "green tribology" was now able to provide full technical support to the preservation of resources and energy, to environmental protection and the improvement of the quality of life of human beings, and even to a reduction in natural disasters (such as earthquakes, mudslides and so forth). It is certainly an important way forward towards a sustainable society [8].

This plenary lecture had the full attention of H. Peter Jost, the founder of tribology and the first President of the International Tribology Council. The next year, the present author was invited by him and Mr. Chris Earnshaw, the then head of the Institution of Engineering and Technology (IET) of the UK, to lead a delegation of the Chinese Tribology Institution on a visit to the UK. The aim was to launch "green tribology" [8, 9]. During the visit, a lecture was delivered by the present author to the Department for Innovation, Universities and Skills (DIUS) of the UK government. There was also a seminar in which the definition, major tasks, and main contents of green tribology were explained. Moreover, he stressed again the importance for the technological progress of tribology, and held that "green" embodied an ideology with which to remodel tribology to "green tribology" [8]. It was in this very period, after repeated deliberations with Jost, that an exact definition of green tribology was determined [9].

Three months later, Jost delivered an opening address titled "Green Tribology - A footprint where economies and environment meet" at the 4th World Tribology Congress in Kyoto [11]. He introduced the definition and main objectives of green tribology and indicated that the expression "Green Tribology" had first been used by Professor Siwei Zhang (the present author) about two years previously. Jost also launched a tribology policy in London on 8 June that year, which date can be regarded as the acknowledged birthday of "Green Tribology" as an international concept [10]. One year later, he emphasized again these viewpoints, and pointed out: "It has since spread rapidly and has become an integral part of tribology in several major countries" [11].

Green tribology has received increasing attention from tribologists. A large number of related articles and a few works/proceedings were published [12,13]. Some major international conferences on tribology also stressed this theme. It is expected that green tribology will extend progress in many aspects.

Research activities related to energy conservation, environmental protection and the improvement of the life quality of human being were dispersed among various disciplines before, such as energy science, environmental science, geoscience, life science and the science of materials, and so forth. This situation greatly hampered the development of research activities and the application of research achievements. Thus, it is hard to meet the needs of sustainable development for economies and society in the new century. The emergence of green tribology adapted to this requirement to unite the related research activities scattered in different disciplines.

Green tribology was also an inevitable outcome, once the economics, science and technology of the human society developed to a certain historic stage. Therefore, its emergence is not accidental at all.

In order to keep abreast of the sustainable development of nature and society, the research subjects of tribology extended to saving energy and materials, reducing emissions, shock absorption, decreasing noise pollution, developing bio- and eco-lubrication and improving the quality of life/existence. It is noticeable that tribology has developed into a new phase, i.e., from the Classical tribology (1966-1999) to Modern tribology (2000-present) [14]. The appearance of green tribology is the chief sign of this new stage.

Green development is a new development model that coordinates the development of the economy, society, and nature, in order for humans and nature to harmoniously coexist. In the current severe situation of resource and energy shortage and ecological environment deterioration worldwide, advocating for green development is of great significance, and green tribology plays a unique role in promoting green development.

1.2 Scope of green tribology

"Green" is also meant as a new mode of thinking, which represents views on ecological balance, environmental protection and improvement of quality of life/existence, and so embodies the ideology of the sustainable development of nature and society perfectly. Green tribology is a main area of modern tribology.

The scope of green tribology could be delimited as the scientific and technological practices which are connected to "resource and energy conservation, ecological balance, environment protection and improvement of quality of life/existence (even including reducing or avoiding the hazard of natural disasters) in two large tribological systems: mechanical system (artificial ecological systems) and non-mechanical system (ecological systems)".

The scope of green tribology not only contains environmental tribology/eco-tribology, tribology for energy conservation and geo-tribology, but also overlaps with related areas such as bio-tribology, biomimetic tribology, green chemistry and green surface engineering, as well as energy science, geoscience, environmental science, science of materials and such. However, green tribology is by no means a loose combination of several research areas or subjects. Hence its scope could not extend willfully.

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CHAPTER 2

FUNDAMENTALS

2.1 Basic concepts of green tribology [1]

2.1.1 Definition and objectives

Green tribology is defined as "the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts" [2-5]. This classical definition is quoted widely nowadays [6-9].

In a strict sense, green tribology is the science and technology, as well as the practices, which are related to saving resources and energy, protecting the ecological environment, reducing or mitigating natural disasters, and improving the existence/quality of life of human beings. It is of benefit to the sustainable development of society and nature.

2.1.2 Social function

The social function of tribology applies to the principles, methods and technologies of tribology that make components, products and systems sustainable man-made eco-systems (sustained artificial ecosystems) in their lifecycle. It is also related to the solving of the various tribological problems related the ecological system and the environment as well as natural disasters, for the purpose of saving resources and energy, realizing ecological balance, improving the quality of life of human beings, and keeping abreast of the sustainable development of nature and society.

Seeing that green tribology is one of the important bases of the sustainable development of nature and society, it might also be termed tribology for sustainability, as stated previously [2].

2.1.3 Basic attributes

According to the general kinetic rules of the development of science and technology, there are two driving forces for the development of green tribology: social demands and the thirst for knowledge. It is known from the definition mentioned above, that green tribology possesses double attributes, namely technique science and engineering technology.

Therefore, it should consist of both green tribo-science and green tribo-technology; that is a couple of inseparable component parts. In this connection, one must be alive to two tendencies. The first firmly believes in green tribology as a science, and thus denies its technical attributes and neglects practical applications. This could cause green tribology to lose the driving force coming from economic developments and social demands. The other view sets its mind on green tribology as being a technology and obliterates its scientific attributes. This viewpoint certainly will cause green tribology to lose its vitality and the scientific basis of sustainable development. Moreover, this view might impede the application of green tribology to non-mechanical systems. Therefore, only if we understand the basic attributes of green tribology comprehensively, can a sustained development of this subject be ensured.

Green tribo-science mainly include theories on reducing vibrations and noise, super lubricity, and zero-wear effect, as well as on friction mechanisms for super-low friction in mechanical systems; the mechanisms of friction that resulted from the natural ecological systems and natural disasters, and so forth.

As to green tribo-technology, it consists of

(1) various sustainable technologies and methods for saving energy and materials, as well as increasing the lifetime of tribo-components and tribo-systems in mechanical systems;
(2) various sustainable technologies and methods for removing or reducing the harmful effects on the ecological environment of mechanical systems, including emissions reduction, zero-emissions, and harmless emissions, and applying ecological lubricants and biomimetic and ecological tribo-materials and so on;
(3) various sustainable tribological technologies and methods for removing or reducing the harmfulness of natural disasters; and
(4) various sustainable tribological technologies and methods for providing technological support to the equipment of both renewable and clean energy [2].

2.1.4 Properties and natures of discipline

Compared with the other tribological branches, green tribology deals with a wider range of disciplines. However, as a branch of tribology, green tribology is also a synthetic discipline. It has two features that are common in tribology (interdisciplinary/multi-disciplinary nature and practical nature) and a feature that is peculiar to itself (sustainable nature/ sustainability).

(1) Interdisciplinary (multi-disciplinary) nature

This means that the research and application are comprehensively applied the theories, methods and technologies of various related subjects. Therefore, in many circumstances, the role and benefits of tribology/green tribology are hard to see on their own and so can be ignored in research as it they often are not the main technique. Also, owing to a lack understanding of this nature, a lot of tribologists do not know that the research and application of tribology/green tribology must be an open, multi-disciplines participant collective activity and not an isolated one of a single subject. As a result, it is difficult to achieve major achievements and notable beneficial results.

(2) Practical nature

This is an element that could be applied to remake the natural world. Hence, only if the practical application is persistent, can tribology/green tribology embody its worth to the fullest extent.

(3) Sustainable nature

This is an element that works for the sustainable development of the natural world and society. This nature is the feature of green tribology that differentiates it from the other branches of tribology. It includes three parts, namely ecological/resources/environmental, economic, and social sustainable, which form an organic whole. The first part is the base, the second is the condition and the last one is the goal. This element turned green tribology into a new field with protruding social functions and notable social benefits.

2.2 Theoretical systems of green tribology [1]

2.2.1 Systems of methodology

The systems of methodology are composed of the following four parts:

(1) Analyses of sustainable nature of green tribological technologies, methods and products. In general, it might be analyzed from three aspects: use of renewable energy, utilization of resources and energy, and ecological impact (discharge of wastes and if the harmless emissions go beyond the draw speed of the biosphere).

However, the fixed quantity parameters and particular method for the assessment of sustainable nature must be investigated further.

(2) Methods of integration and coupling of different green tribo-techniques.

(3) Application of life cycle assessment (LCA) to green tribology, namely an approach of life cycle thinking (economic and ecological thinking). LCA addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end of life, recycling, and final disposal [10], the so-called "cradle to grave" approach. It involves three aspects of the ecological and environmental systems: health of mankind, quality of environment, and resources.

(4) Assessment indices for the application of green tribo-science and tribo-technology, which consist of two parts:
(a) Resource, energy indices: type, sustainable nature, utilization ratio, rate of recovery and reprocess ratio, and such;
(b) Environmental indices: discharge level of wastes, serious degree of noise and vibration, and so on.

2.2.2. Discipline composition and structure systems

(1) Discipline composition

Green tribology has two branches. In the first the research and application of green tribology are just part of the research objectives, such as in tribology for energy conservation and ecological/environmental tribology. The second uses the principles and methods of green tribology to study a specific object, such as green nano-tribology [11], tribology for green equipment (such as green ship [12], green automobile and green energy equipment) and natural disaster tribology. Natural disaster tribology mainly investigates the role and mechanisms of tribology in natural disasters (including meteorological disasters, geological disasters and marine disasters and so forth).

(2) Structure systems

The structure systems of green tribology include the basic framework, the administrative structure, the originated logical unit (or "starting point"), and the overall logical structure. The basic framework consists of three essential factors (research objectives, connotations of discipline, and social functions) of green tribology (Fig. 2-1).

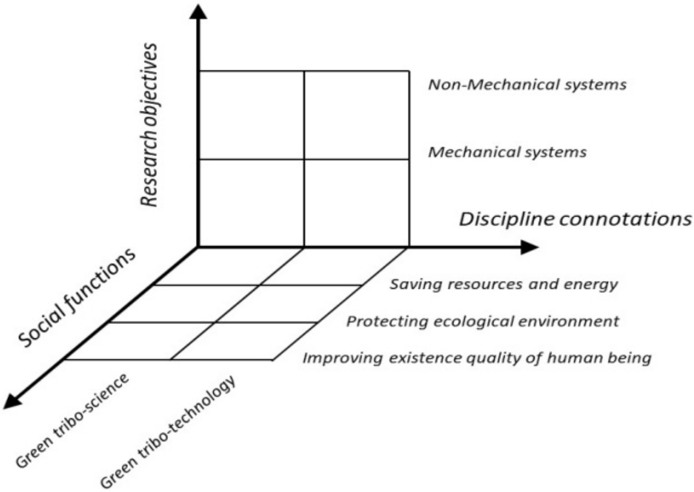

Fig. 2-1 Basic framework

The second branch of green tribology can be divided into three different scales, namely green micro-tribology, green macro-tribology and green universe tribology, which together form the administrative structure of green tribology *(Fig. 2-2)*.

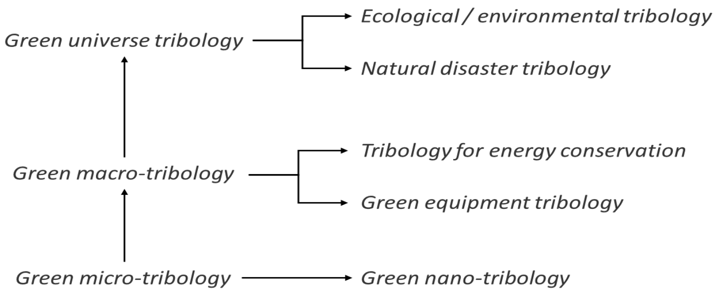

Fig. 2-2 Administrative structure

Friction can be considered as the "source" of tribology/green tribology. This character could provide tribology/green tribology with infinite vitality, thus creating the widest developed space and lasting developed prospects. Therefore, "friction" might be taken as the logical starting point or "originated logical unite" of the logical structure of tribology/green tribology *(Fig. 2-3)*.

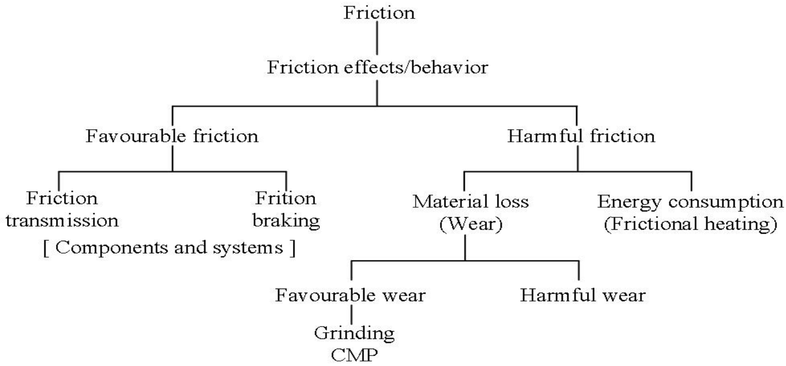

Fig. 2-3 Originated logical unite

Synthesizing the contents of the above sections, the overall logical structure could be constituted through spreading out the inner relation of the three factors of the basic framework with a certain logical order. It consists of four parts: research objectives, discipline connotations, social functions and assessment indices (Fig. 2-4).

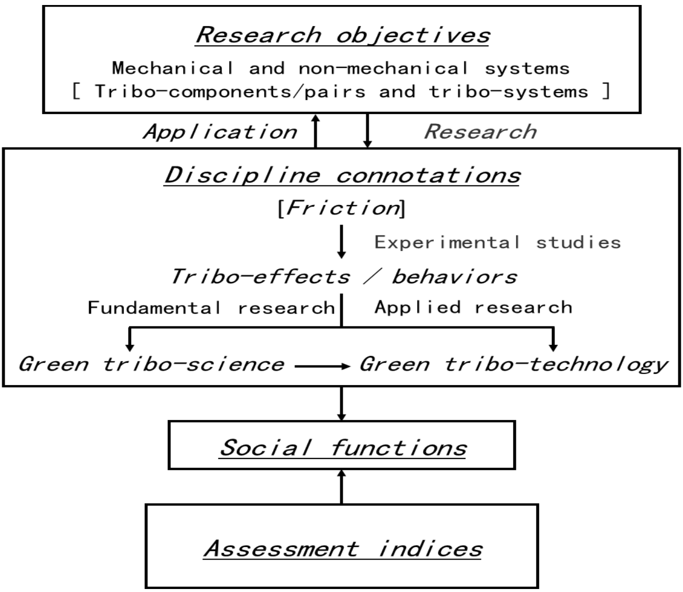

Fig. 2-4 Overall logical structure

The construction of a theoretical system based on the fundamentals of green tribology is a pioneering work, with no mode or method to be consulted. It is just a preliminary exploratory investigation and must be improved unceasingly so as to be perfected. A theoretical system could be conducive to seizing the developing directions of green tribology, and to opening up the strategic fields of research, thereby promoting overall and sustainable development of green tribology.

2.3 General axioms of green tribology

Based on the basic concepts and applied criteria of green tribology, the general axioms could be deduced and regarded as the guides for research on and application of green tribology.

(1) Saving the resources (including energy, raw and processed materials) of tribo-components and tribo-systems.
From the point of view of tribology, any mechanical component or machine can be regarded as a tribo-component of the tribo-system. Their working life reflects the utilization ratio of resources, and the efficiency of a machine reflects the utilization ratio of energy directly. Friction is the prime culprit for energy being used up, and wear is the main origin for the expenditure of materials.
The best way to increase the working life of mechanical parts and machines is to adopt various sustainable technologies and methods, such as wear-resistance and zero-wear techniques. To increase the utilization ratio of energy for tribo-systems, various sustainable technologies and methods of friction-reducing must be applied, including super-low friction, super-lubricity and eco-lubrication techniques. Also, a good tribological design method will contribute to the improvement of both the lifetime and the energy utilization ratio of a machine, including the optimized design of the lubrication system.

(2) Avoiding or reducing harmful discharges of tribo-components and tribo-systems.
This means that the tribo-components and tribo-systems of mechanical systems must have the smallest environmental burden. To this end, it is vital to stubbornly reduce the discharge level of wastes and to achieve zero-emissions and harmless emissions. Harmless emissions means not only no emission of wastes, but also that the discharge of harmless wastes must not go beyond the speed of absorption and digestion of the biosphere.

(3) Improving the health and the quality of life/existence of human beings.
Wear control is importance for human health as the impact of wear particles in the air, water and land on human health can be obvious instantaneously.
(4) Avoiding or reducing the occurrences of natural disasters.

2.4 Connotations (research contents)

The connotations are expounded through some typical or representative researches.

2.4.1 Sustainable tribo-techniques for the saving of energy and materials, and increasing of the lifetime of the tribological parts and tribo-systems

Sustainable tribo-techniques must have the highest efficiency of the machines and the lowest discharge levels of waste.

(1) Technologies for improving the fuel economy of engine systems

Environmental impact and energy consumption have made the improvement of the fuel economy of engine systems an important issue. For this purpose, new lubricants were developed, such as PAO (Polyalpholefin)-based lubricants [13] and new types of synthetic esters [14].

Friction reduction is the most important measure for improving the fuel economy of engine systems. Hayasi and Fuwa have pointed out seven approaches for friction reduction [15]:

Lower viscosity oil
Lower load design
Smoother surface design
Lower friction oil by friction modifier
Lower friction materials
Lower traction oil
Lower drag design

In addition, DLC-Si coating with diesel fuel lubrication has a larger effect on friction reduction than coating with engine oil lubrication [16].

A super-low friction torque tapered roller bearing (TRB) applied to the rear axle differential for passenger cars was developed [17], which obtained a friction torque reduction of up to 75% compared with the conventional low friction torque TRB. Its three features are shown in Fig. 2-5.

A new nanoparticle-modified polyetheretherketone (PEEK) composite was used as the thin coating for hybrid bushings in automotive aggregates [18]. It exhibited a much lower coefficient of friction and specific wear rate in comparison to the commercial product, leading to a pronounced reduction in fuel consumption and a better engine efficiency.

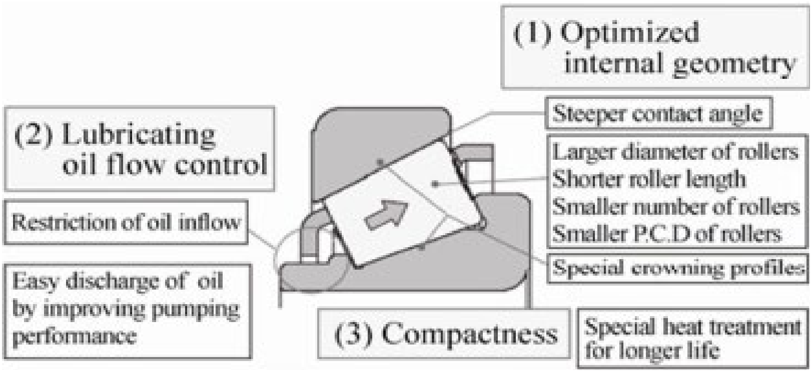

Fig. 2-5 Features of developed tapered roller bearing (TRB) [17]

(2) Technologies for super-low friction and wear resistance

A novel fullerene-like hydrogenated carbon film was prepared by pulse bias-assisted plasma enhanced chemical vapor deposition, and its mechanical and tribological properties were investigated [19]. This film exhibited super-low friction and wear in both dry inert and humid ambient atmospheres and less sensitivity to H2O and O2 molecules in air.

The mechanism responsible for excellent tribological properties in AlMgB14-TiB2 nanocomposite coatings was identified as oxidation of the TiB2 phase and subsequent reaction of the oxide with moisture to produce a surface layer of boric acid, B(OH)3 [20]. These coatings show sustained friction coefficient values as low as 0.02 in water-glycol-based lubricants and offer a unique combination of excellent wear resistance and low friction when combined with the high hardness of the mixed-phase composite (30–35 GPa).

The wear behaviors of ultra-high molecular weight polyethylene (UHMWPE) coated with hydrogenated diamond like carbon (DLCH) layers were investigated [21]. It was found that the surface hardness and the wear resistance of coated materials were increased compared to that of an uncoated one. The DLCH coatings could be a potential method to reduce backside wear in modular implants.

2.4.2 Sustainable tribo-techniques for removing or reducing the harmful effects on ecological balance (including human health) produced by both tribological parts and tribo-systems in the course of a lifecycle

(1) Eco-/bio-lubricants

Environmental issues are leading to a growing interest in eco- and bio-lubricants. The perfect eco- and bio-lubricants should be eco-non-toxic and bio-degradable quickly, and capable of sustainable large-scale production.

The SAPS (sulfur and phosphorus)-free additive KWF-012122 derived from natural resource "amino acids" was developed [22]. Use of chitin, chitosan, and acylated derivatives as thickener agents of vegetable oils has been explored [23].

Sliding friction was analyzed for titanium covered with mixed biofilms consisting of Streptococcus mutans and Candida albicans [24]. The structure of biofilms consisted of microbial cells, and their hydrated exopolymeric matrix acts as a lubricant. Very low friction was found on titanium immersed in artificial saliva and sliding against alumina in the presence of biofilms. This result is of particular significance for dental implant connections and prosthetic joints.

Hydration lubrication is a new area explored. Klein [25] pointed out that combining the supramolecular benefits of polymer brushes together with the highly hydrated nature of zwitterionic phosphorylcholine monomers could provide important advantages in designing extremely efficient boundary lubricants.

Much research on and development of new bio-based metal working fluid based on various vegetable oils have been engaged. From the viewpoint of the qualities required of metal working fluids, the advantages and disadvantages of vegetable oils as lubricants are listed *(Table 2-1)* [26].

Winter and coworkers [27] described the use of ecologically benign lubricants as cutting fluid and hydraulic fluid. They analyzed the usability and resulting technological and ecological consequences of water miscible biopolymers as a substitute and confirmed the good performance of the polymer fluid as an optimal ecologically benign lubricant for metal processing and hydraulic systems.

Tribological study and case analyses of the elastomeric bearings lubricated with seawater for marine propeller shaft systems were conducted [28].

Table 2-1 Advantages and disadvantages of vegetable oils [26]

Advantages	Disadvantages
High biodegradability Low pollution of the environment Compatibility with additives Low production cost Wide production possibilities Low toxicity High flash points Low volatility High viscosity indices	Low thermal stability Low oxidative High freezing points Poor corrosion protection

(2) Biomimetic tribological materials and tribo-techniques

As living beings have natural adaptability to ecological environments, biomimetic tribological materials and tribo-techniques have become an important area of green tribology.

In the Huya River hydropower station in China, the concrete hydraulic construction (floodway) is destroyed seriously every year owing to the water-head being up to 280 m in flood season. To obtain a better adhesive erosion-protection surface on the hydraulic construction (flood-way concrete structure), UHMWPE (ultra-high molecular weight polyethylene) was selected as an erosion-resistance material under a high sand-content slurry impact condition, and a bionic surface structure based on the epidermis of sandfish and the clamp of a dragonfly's wing was developed by Jian Li and Chengqing Yuan *(Fig. 2-6)*. This technique has provided the concrete structure with good protection after three flood seasons *(Fig. 2-7) (Personal communication, 2010)*.

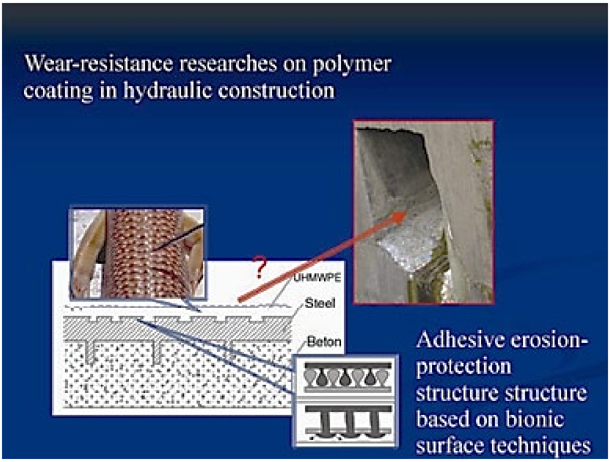

Fig. 2-6 Bionic surface structure based on the epidermis of sandfish and the clamp of dragonfly’s wing

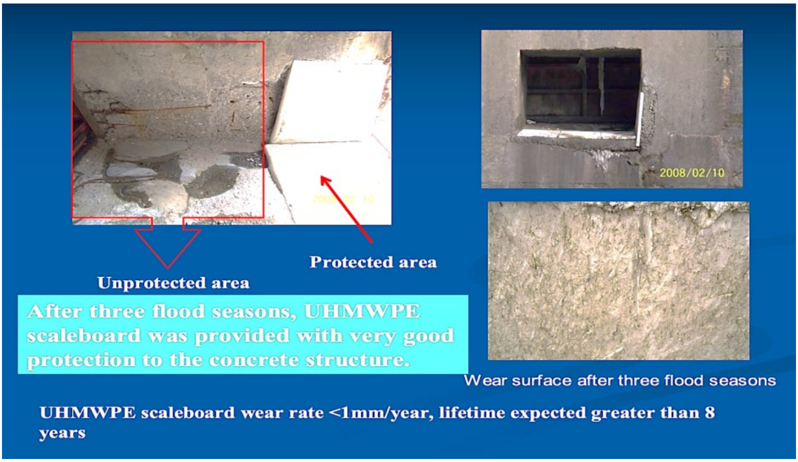

Fig. 2-7 Wear surface after three flood seasons

The mechanisms of sand erosion resistance of the desert scorpion (and roctonus australis) were investigated to improve the erosion resistance of tribo-components [29]. It was found that the functional surfaces used for sand erosion resistance of the desert scorpion were constructed by special micro-textures such as bumps and grooves.