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**[Invited Paper]**

# Environmentally friendly tribology (Eco-tribology) †

Shinya Sasaki*

*Department of Mechanical Engineering, Tokyo University of Science,*
*1-14-6 Kudankita, Chiyoda, Tokyo, 102-0073, Japan*

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**Abstract**

The Earth is facing many serious environmental problems. The global warming problem has reached a point at which action cannot be delayed. It is necessary not only to expect novel technological development but also to create realistic solutions by extending conventional technologies. Tribology has supported various technological developments over the years and has also responded promptly to societal demands for decreasing substances from engineering products that would be hazardous to the environment. As societies aim to become sustainable, tribology needs to be involved and contribute to the solution more than ever before. Environmentally friendly tribology, eco-tribology, through progress in surface modification, is seen to be an effective engineering technology that can contribute very much to sustainable societies. Multi-scale surface texturing, which is a new concept of surface modification for tribo-materials, and diamond-like carbon (DLC) coating technology were introduced as the expected future development.

*Keywords*: Sustainable; Environmentally friendly; Tribology; Surface modification; Surface texturing; Diamond like carbon; Ionic liquid

## 1. Introduction

The Earth is facing many serious environmental problems. Global warming and environmental pollution have been progressing constantly as shown in Fig.1 [1]. How should tribology deal with these problems? How much can tribology contribute to solving these problems is a question that is often asked. Tribology has supported various technological developments over the years, such as improving the energy efficiency and durability of vehicles, household appliances, industrial machines and plants. Tribology has also responded promptly to societal demands for decreasing substances from engineering products that would be hazardous to the environment, which has included abolishing asbestos from vehicle brake systems, replacing refrigerants with CFC-substitutes, and controlling the lead used in bearings. As societies aim to become sustainable, tribology needs to be involved and contribute to the solution more than ever before. Environmentally friendly tribology, eco-tribology, through progress in surface modification, is seen to be an effective engineering technology that can contribute very much to sustainable societies. This paper introduces multi-scale texturing and DLC as the expected surface modification technologies in the future.

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*Corresponding author. Tel.: +81 3 5228 8389, Fax.: +82 3 5228 8389
E-mail address: s.sasaki@rs.kagu.tus.ac.jp



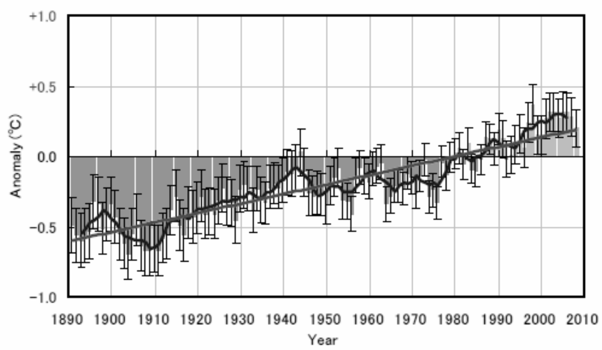


Fig. 1. Annual anomalies in global average surface temperature from 1981 to 2008 [1].

## 2. History of eco-tribology

The 1st tribologist was recorded in Egypt at about 2400 BC. At that time, the energy source was only renewable natural energy. The lubricant was a biodegradable substance such as water, wine, vegetable and animal oil. People's lives were environmentally friendly.

Since the Industrial Revolution in about 1760, coal has come to be used as an energy source. The concentration of carbon dioxide in the atmosphere started rising from this time. In addition, the energy source took the place from coal to oil in around 1930. The atmospheric carbon dioxide concentration had come to increase rapidly with the prosperity of the petrochemical industry. A substantial change also happened to tribology. Mineral and synthetic oils came to be used in place of the carbon neutral material such as a vegetable oil as for lubricants.

In 1966 with the publication in England of the "Department of Education and Science Report," sometimes known as the "Jost Report," the word "Tribology" was introduced and defined as the science and technology of interacting surfaces in relative motion and of the practices related thereto. The Jost report also claimed that industry could save considerable money (50 billion pounds) by improving their lubrication, friction and wear practices. However, "eco" of eco-tribology meant not ecological but economical at this time.

The climate change by green house effect came to be admitted in a scientific manner, and the Kyoto Protocol was adapted at the COP3 in 1997. The proportion of ecology in Eco-tribology rose more than economy against the background of the rise of people's concerns to environmental problems. In addition, the global economic crisis in 2008 brought a big influence for eco-tribology also. The role of an environmental performance has grown as an important factor deciding the product's value. Ecology and economy, which had been indicating the conflicted directions, became with the same meaning for eco-tribology now.

## 3. Topics related to eco-tribology

### *3.1 Tribo-materials*

Tribo-materials are expected to control friction and wear properties, lighten machine elements, improve recyclability, etc. Moreover, the use of materials like lead, which have detrimental effects on the environment, is limited by RoHS compliance. Surface modification technology such as surface texturing and coating will help create an effective solution to meet the demand for environmentally safe approaches. Figure 3 shows the micro-grooved bearing (MGB) developed by Taiho Kogyo Co. Ltd., Japan [2]. The MGB, which is a lead-free engine bearing with regular fine grooves in the circumferential direction on the bearing inner wall, has superior characteristics, which include high resistance to seizure and fatigue, as compared with conventional plan bearings [3].

Diamond-like carbon (DLC) coating technology has advanced remarkably in the last 10 years. DLC coatings, which have some tribological advantages with their high hardness, surface smoothness and chemical stability, are already being applied as low frictional tribo-materials to some automobile and industrial machine parts. Nissan Motor Co. Ltd. has developed a hydrogen-free DLC coating and has succeeded in improving the fuel economy of a V6 engine markedly by applying this coating to the valve lifter [4]. Additionally, DLC films are chemically inert, a property that is expected to be utilized for controlling the decomposition of the lubricant on the sliding surface [5].

### *3.2 Lubricants*

Lubricants greatly contribute to decreasing frictional losses in mechanical systems. It is expected that low-viscosity, long-life oils will be developed with advanced additives such as friction modifiers and anti-wear, anti-oxidation agents. Research on decreasing the detrimental impact of lubricants on the environment now encompasses such topics as halogen-free and biodegradable oils, carbon-neutral vegetable oils, the minimum quantity of lubrication (MQL) [6] and process fluid lubrication such as water lubrication [7].

### *3.3 Machine elements*

Energy reduction has rapidly progressed in the last few years through the use of machine elements such as roller bearings and journal bearings. For example, the use of a new automotive transmission bearing has successfully reduced rotational torque 75 percent by improving the sliding resistance between the roller end and the retainer pocket face as shown in Fig. 4 [8]. Such renovations of individual tribo-elements enable innovations throughout entire systems.

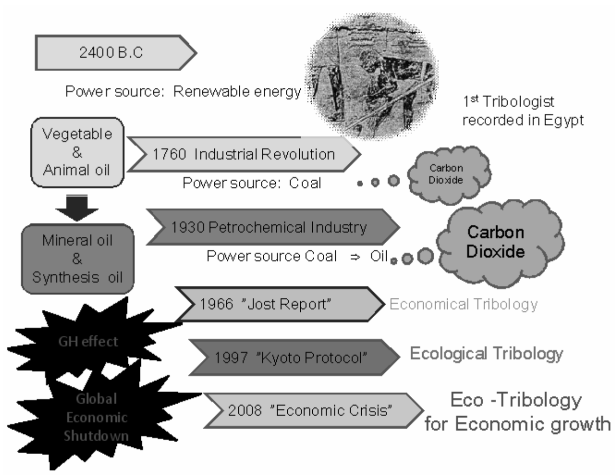


Fig. 2. History of Eco-tribology.

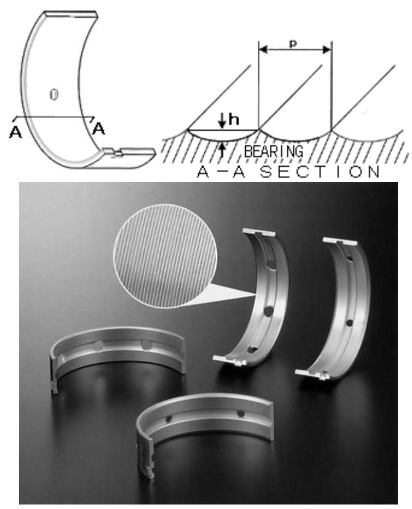


Fig. 3. Lead-free Micro-Grooved Bearing (Taiho Kogyo Co. Ltd) [2].

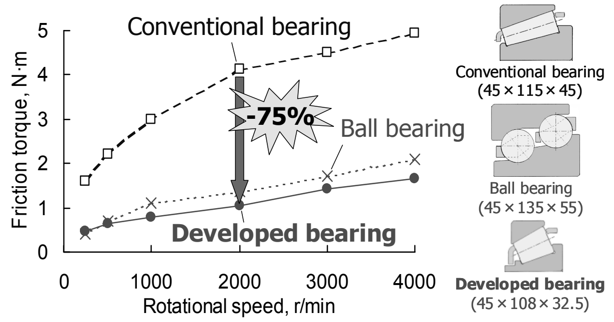


Fig. 4. Torque comparison of developed bearing to conventional and ball bearings designed to have same calculated life (JTEKT) [8].

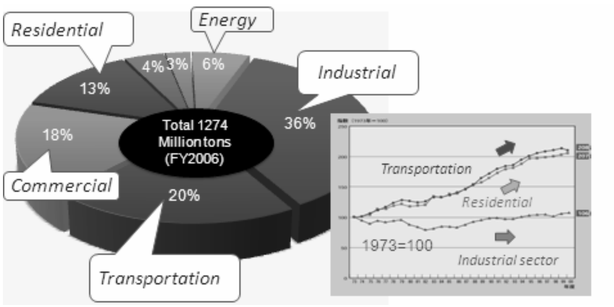


Fig. 5. Breakdown of carbon dioxide emissions in Japan.

Automobiles are considered to be a typical example of a tribo-system that includes the engine, transmission, tires, etc.

### 3.4 Tribo-systems

The transportation sector accounts for 20 percent of total carbon dioxide emissions in Japan as shown in Fig.5. Improving the energy efficiency of automobiles, which account for 90 percent of the vehicles used in transportation, is the most effective means of reducing total carbon dioxide emissions. The household appliances sector accounts for 15 percent of total carbon dioxide emissions and it has been increasing in recent years. However, the energy efficiency of air conditioners and refrigerators has improved greatly over the past decade, and tribology has contributed to improving the performance the compressors that are the core technology used in these appliances [9].

Mitsubishi Heavy Industries, Ltd. has developed a new seal technology for stream turbine, which includes a leaf seal (Fig.6 [10]) that minimizes leakage loss from steam turbines and a new type of clearance control technology that reduces seal fin friction to a minimum. They said that the new technology can be expected to raise performance by approximately 0.6-2.4% depending on the operating and maintenance conditions of each turbine [11].

### 3.5 Maintenance tribology

Maintenance tribology contributes not only to increases in production efficiency but also to waste control of resources and energy [12]. It is necessary to systematize eco-tribology by involving and integrating the concepts of life cycle tribology (LCT) [13] and eco-design based on maintenance tribology.

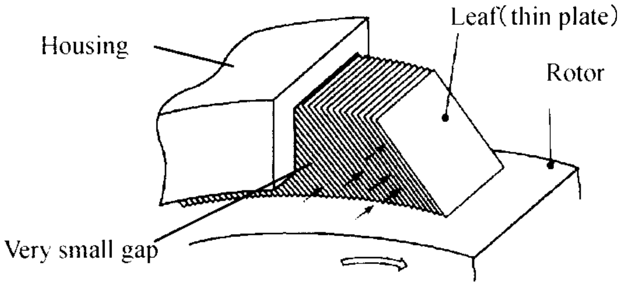


Fig. 6. Structure of the leaf seal (MHI Ltd.) [10].

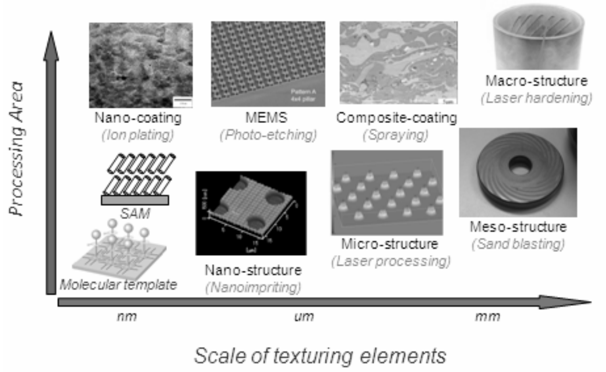


Fig. 7. Variety of material processing for multi-scale surface texturing.

## 4. Prospect of surface modification for Eco-tribology

### 4.1 Multi-scale surface texturing

Multi-scale surface texturing is a new concept of surface modification for tribo-materials. Making use of the tribological phenomenon that becomes predominant at each scale level, multi-scale surface texturing aims at improving the total performance inclusively by architecting the surface structure on a consecutive scale from the nano-micro level to the macro level. Figure 7 shows a variety of surface structures and the processing related to the size of the texturing element and processing area. It starts from molecular modification on the surface using super molecules and self-assembled monolayers (SAMs), and there are various processing methods such as nano-particle and/or multi-layer composite coatings, nano-imprinting, MEMS, sandblasting, laser ablation, precision machining and laser hardening. It will be very important in the future to create the multi-scale surface texture by combining two or more of these processing methods.

As for water lubrication of ceramics, this application has been sought for about 20 years with the discovery of a low-friction phenomenon. However, it has not seen wider use due to the problematic frictional property in the low sliding speed region. Micro-laser processing has also been adapted for forming dimple patterns on silicon nitride surfaces to improve the friction characteristics. Figure 8 shows an example of improve

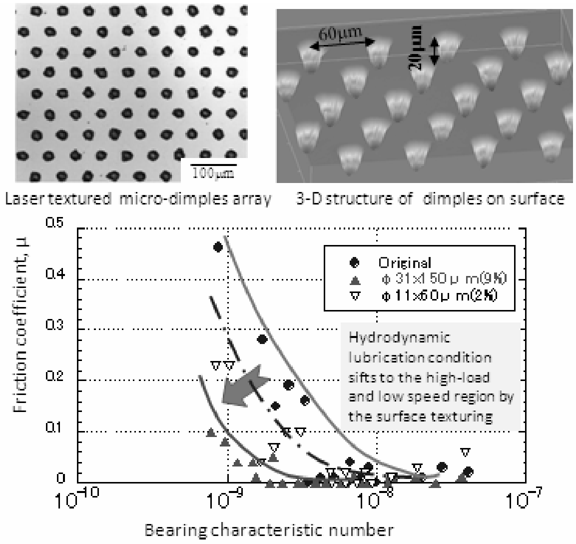


Fig. 8. Water lubrication of surface-textured ceramics.

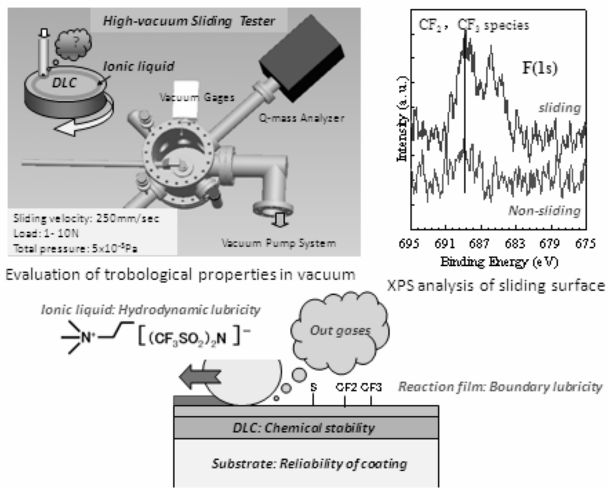


Fig. 9. Lubricity of ionic liquid for DLC.

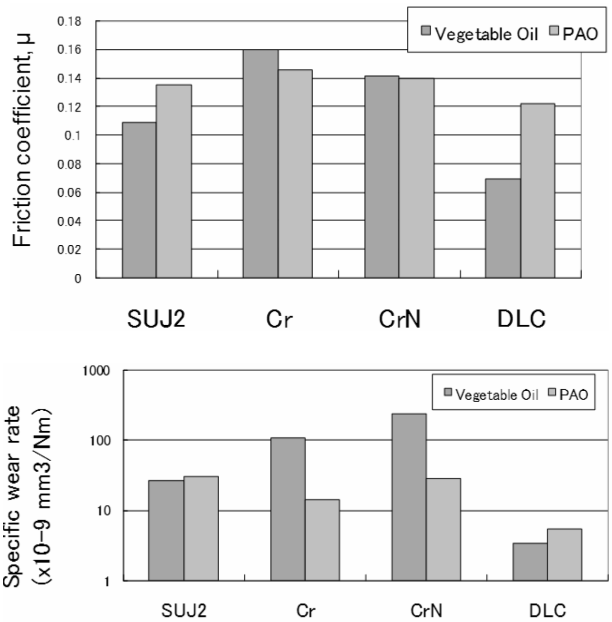


Fig. 10. Lubricity of vegetable oil for hard coatings(SRV sliding tester, Ball on Disc, 50N, 50Hz, 1mm, 50C).

ing the sliding characteristics by surface texturing [14].The range of the hydrodynamic lubricating condition was shifted to a small bearing characteristic number region of higher load and lower sliding velocity. This expansion of the hydrodynamic lubrication range is thought to have been achieved on medium-sized dimple structures which generated higher hydrodynamic pressure and protected the sliding surface from abrasive damage by the wear particles. However, many uncertainties remain with regard to the hydrodynamic pressure generation mechanism on textured surfaces. It is expected that a design manual will be created for optimizing multi-scale surface textures by applying the computational fluid dynamics (CFD) method.

### 4.2 DLC coatings for green lubrication

Ionic liquids have received attention for their use as environmentally friendly solvents (green chemistry). Ionic liquids are expected to see use as a novel lubricant because they have unique properties that include non-volatility, thermal stability and electrical polarity [15]. By combining each of the advantages of ionic liquids and DLC coatings, we have started to develop a novel tribo-system for high-vacuum sliding applications [16]. We evaluated the tribological properties of DLC coatings under lubrication with an ionic liquid using a high-vacuum pin-on-disc sliding tester. During the sliding tests, we used a Q-mass analyzer to monitor the friction coefficient and the residual gases as shown in Fig. 9. The ionic liquid exhibited stable friction coefficients compared with dry sliding. XPS analytical results revealed that S and F elements were present on the sliding surface compared with non-sliding surface. We think that the lubricity of the ionic liquid depends on the tribo-chemical reaction product between the ionic liquid and the DLC sliding surface. On the other hand, the tribo-chemical reaction on the sliding surface causes gas generation with the decomposition of the ionic liquid molecules. There was not much gas emission, and the influence on the total pressure was slight. It is very important to control a moderate tribo-chemical reaction that balances the lubricity and the emission of the decomposition gases by selecting the kind of ionic liquid and the combination of the ionic liquid with the tribo-materials.

Vegetable oil, which has been used as a lubricant from ancient times, is a representative green lubricant that is carbon neutral, biodegradable and safe for human health. However, it is hardly used now because its anti-oxidation and durability performance are inferior to mineral oils and synthetic oils. Recently, the wider use of DLC as a tribo-material has brought about the possibility of using vegetable oil as a lubricant. Triacylglycerol contained in vegetable oil is understood to have excellent lubricity for DLC as shown in Fig.10. Moreover, DLC features corrosion resistance while the oxidation of the vegetable oil is controlled on the chemically inert sliding surface of the DLC. Such a green lubrication system is expected to see use in food machines.

## 5. Conclusions

The global warming problem has reached a point at which action cannot be delayed. The Japanese government has announced a challenging target: by 2020 reduce greenhouse gas emissions by 25% compared with 1990. To achieve such a high objective, it is necessary not only to expect novel technological development but also to create realistic solutions by extending conventional technologies. Eco-tribology, through progress in surface modification, is seen to be an effective engineering technology that can contribute very much to sustainable societies.

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**Shinya SASAKI** received his BS, MS and PhD degrees from Tokyo Institute of Technology, Japan, in 1984, 1986 and 1991, respectively. He worked for National Institute of Advanced Industrial Science and Technology, AIST, Japan as a senior researcher for 21 years from 1986. He is a professor in the Department of Mechanical Engineering at the Tokyo University of Science, Tokyo, Japan. His current research interests include surface design, surface modification and tribology for eco-products and sustainable societies.