Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science
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Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 2012 226: 347 originally published online 11 November 2011
DOI: 10.1177/0954406211428020

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The manuscript was received on 1 May 2011 and was accepted after revision for publication on 6 October 2011.

DOI: 10.1177/0954406211428020

Abstract: This concept paper analyses current nanotribology regarding its potential to go green, and presents promises and possible pitfalls of such an approach. It introduces the basic aspects of green nanotribology: nanosurfaces, nanoagents, and nanoprocesses. These basic aspects are analysed in light of three questions: How can processes get more environmentally sustainable with nanotribology? How to prevent processes to turn worse because of adverse chemical reactions? And, how to prevent that the resulting green nanotribology is not only upfront 'green' and negative impact on the environment and organisms and ecosystems is only transferred to other layers? Biological best-practice green nanotribological systems, structures, and processes are identified and serve as an inspiration to address the above questions and establish a path towards green nanotribology, sustainable, efficient, and innovative.

Keywords: green tribology, biotribology, bioinspiration, biomimetics, environment-friendly tribology, bionanotribology, biomimicry innovation method, green nanotribology, nanostructures, nanoagents, nanoprocesses, nanosurfaces, sustainability, innovation

1 INTRODUCTION

Tribology is defined as the science and technology of interacting surfaces in relative motion, which involves friction, wear, and lubrication. Various aspects of interacting surfaces in relative motion have been the focus of tribology, including the tribology of automotive applications, microelectromechanical systems (MEMS), magnetic storage devices, adhesive contacts, micro/nanotribology and biotribology. Nanotribology is a relatively new field that uses nanotechnological methods to deal with friction, wear, and lubrication of interacting surfaces in relative motion, with the ultimate goal to boost performance of tribosystems. The development and wide availability of scanning probe microscopy techniques paved the way for nanotribology, and most of the early players are at home in both fields. Note that nanotribology introduces nanotechnological methods to tribological systems, and does not automatically imply tribology of nanosystems.

In the course of this article, the history of green tribology is reviewed in Section 2, including the initial players and publications. Subsequently, the concept of green nanotribology is defined. In the next step, it is first generally shown how improved energy management influences the tribosystem and second, how this can specifically be achieved regarding green nanotribology and what can be learnt in this respect from nature. Optimization levers in nanotribology (i.e. breaking-in, additives, finishing, and material selection) are treated in Section 3. Wherever possible, examples are drawn from outstanding natural tribosystems, such as the synovial joints of the hip and the shoulder, which exhibit amazingly low friction constants (see [**1**] for a recent publication on a new mechanism in lubricating film formation involving model synovial fluids) or biological monomolecular lubricant layers providing boundary lubrication *in vivo* [**2**]. Section 4 deals with goals for effective green nanotribology (and how they can be achieved) and outlines an innovation method that allows for principle identification and transfer from successful biotribological systems to tribology. Examples for biomimetic surfaces are superhydrophobic and self-cleaning surfaces [**3**, **4**] inspired from the hierarchical roughness features found on the lotus leaf surface that increase the contact angle of water droplets [**5**] or gecko-tapes [**6**] inspired by the high and adaptive adhesion of the gecko foot that is based on hierarchical structures down to the nanoscale that interact *via* the short-range van der Waals forces with the environment [**7**]. The article concludes with an outlook that stresses the importance to bridge the gaps between inventors, innovators, and investors, by establishing a pipeline from knowledge *via* prototypes to products.

2 GREEN TRIBOLOGY

The president of the International Tribology Council, H. Peter Jost, addressed at the 5th World Tribology Congress in Kyoto in September 2009, the situation surrounding the world and tribology, with a strong emphasis on green tribology, declaring:

> Green tribology is the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts. Its main objectives are the saving of energy and materials and the enhancement of the environment and the quality of life. [**8**]

Jost, who introduced the term 'Tribology' in the 1960s, outlined in Kyoto that there were now production requirements concerning the supply of energy, mineral resources, and food in a way which had not been known before. A focus on tribology might give 'breathing space' while comprehensive solutions to environmental problems were being addressed and he suggested that tribology must fall in line with the major politics of world environment and energy.

Si-wei Zhang, past chairman of the Chinese Tribology Institution, coined the term 'Green Tribology' and launched it as an international concept in June 2009. The reason Si-wei Zhang suggests that 'Green Tribology' might be one of the key directions of technological progress of tribology is that in a major investigation commissioned by the Chinese Academy of Engineering concerning economic benefits derived from the application of tribology, economic benefits of 1.55 per cent GNP, with estimated 60 per cent of this figure related to energy savings mainly acquired by reducing the consumption of both energy and materials. For the UK, as stated by H. Peter Jost, the economic benefits would be £8–10 billion, out of which 60 per cent to 70 per cent would be energy related, all this largely from existing and applied research (innovation).

In 2010, Michael Nosonovsky and Bharat Bhushan [**9, 10**] edited a theme issue of the *Philosophical Transactions of the Royal Society A* on the subject, and a related book is scheduled to be published by Springer in 2012. The field 'Green Tribology' is currently in the final steps of definition.

2.1 Green nanotribology: Definition and concept development

Green nanotribology utilizes nanotechnology to establish specific conditions regarding friction, wear, and lubrication of interacting surfaces in relative motion to achieve minimum environmental impact.

Green nanotribology includes sustainable control of friction, wear, and lubrication on the nanoscale, environmental aspects of nanoscale lubrication layers and nanotechnological surface modification techniques, nanotribological aspects of green applications such as artificial photosynthesis [**11**] and sustainable biomimetic tribological nanotechnology. Green nanotribology shall provide technical support to preservation of resources and thoughtful energy usage, and to advance society forward towards sustainability. Biomimetics [**12**, **13**] is an important concept in the development of green nanotribology as it provides a constant source of inspiration by analysing materials, structures, processes, and systems from practical examples successfully performing in living nature; the deep underlying principles are identified and subsequently transferred to science, technology, or the arts. Biomimetics in tribology is a growing field [**9**, **14–19**]. Nachtigall [**20**] reports general principles that can be applied by engineers who are not at all involved in biology: integration instead of additive construction, optimization of the whole instead of maximization of a single component feature, multi-functionality instead of mono-functionality, energy efficiency, and development *via* trial-and-error processes. Systematic technology transfer from biology to engineering thereby becomes generally accessible.

However, biomimetics is not inherently green (i.e. minimized environmental footprint) or sustainable (i.e. optimized use of available resources):

> . . . the increasing popularity of biomimetics is also due to a common misunderstanding of biomimetic technologies being directly linked to sustainability and thus 'greener' than any other innovation method. It is beyond controversy that the discussion of nature and natural technologies delivers an increased knowledge and consciousness about ecological interconnections, but as researchers have argued again and again, biomimetics as a sole innovation tool can also deliver unsustainable products and is not a panacea for all global problems. The intention to design environmentally responsible and sustainable products is independent of this design method. The values according to which applications are designed come from outside

> referring to societal and cultural norms. This will not change in the future, which means biomimetics will still be an innovation method, characterized by the strategic information transfer, independent of a value system. [**21**]

Nanotribology deals with *nanosurfaces*, *nanoagents* (ingredients, additives), and *nanoprocesses* (Table 1); all these three components need to be taken into account in the concept development of green nanotribology. Nanosurfaces are two-dimensional entities used in tribology that aim at adding additional functionality to the tribosystems *via* the physical properties of the interfaces (as opposed to bulk chemistry). In nanoagents, which are three-dimensional functional nanoparticles, the added functionality is locally achieved *via* surface structure and physical properties. Nanoprocesses are specifically adapted classical tribological processes that utilize nanosurfaces and nanoagents to enhance the performance of the tribosystem.

In various tribological applications, harmful additives are used. Turning nanotribology green, however, would not only imply the usage of green additives. Tribology is a systems science, and therefore, also the environment and development with time have to be accounted for. Nanoagents in tribology are additives, products of the additives, and byproducts that appear in the system after the technological application. Sustainability regarding the nanoagents can be ensured if the reaction products (which can be harmful) are either chemically inert after use or are fed back to the system for further usage ('waste-to-wealth' concept). Post-process nanoagents need to be either intended, inert or fed back to the reaction.

Table 1. Nanotribology agents, their respective importance in going green and points to address for achieving green nanotribology

Nanotribology	Importance	Points to address
Nanosurfaces	Medium	Nanostructured surfaces Hierarchical surfaces Material selection Coated materials Monomolecular lubricant layers
Nanoagents	High	Physical properties Chemical properties Effect on environment and biology Changes in properties with time Changes in properties in the triboprocess
Nanoprocesses	Medium to low	Energy efficiency Share between process-relevant energy, destructive energy, and waste and reusable energy Effectiveness of reusing process energy

Furthermore, potential harmful byproducts that have nothing to do with the initial nanoagent need to be either neutralized or used further.

Three basic questions need to be addressed when turning the nanoagent green:

1. Is the agent in itself green?
2. Are the reaction products that the agent turns into at use or after use harmful?
3. Are the process parts green?

Independent of the agent and its reaction products, it needs to be ensured that all non-green parts are properly taken care of in the process (reused, neutralized, recycled). Risk assessment of nanotechnological materials, structures and processes can be of great help in this step [**22–31**]. A further question to address is: do any harmful products appear in the process by the use of nanotechnology?

2.2 Energy balance in a tribosystem

Only a certain part of the energy put into a tribological process (Fig. 1) is used as process-relevant energy. A major portion is non-process-relevant energy (destructive energy, waste energy, and reusable energy; Fig. 2).

Tribology deals with minimization of the effects of the destructive energy and aims to maximize the share of process-relevant energy (Fig. 3). Within the non-process-relevant energy share, the tribosystem designers shall aim to maximize the share of reusable energy (energy management efficiency) and the actual proportion of energy reused (effective energy management). This can happen *via* energy harvesting, cogeneration (waste heat recovery), or energy containment (keep process energy in the system, cf. diesel engine). An optimized energy balance reduces

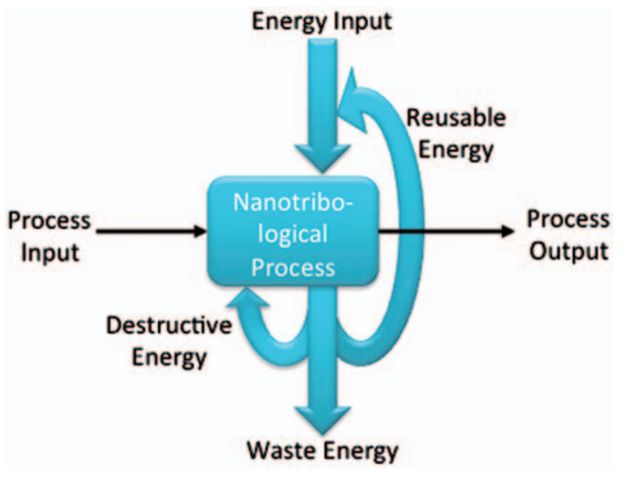

Fig. 1 Generalized nanotribological process

the environmental impact and is therefore of relevance in green (nano)tribology.

By tribosystem energy optimization, the total energy required for the same output is reduced. An example for this is shown in Fig. 3. In this system, the initial process-relevant energy share is 15 per cent. Destructive energy amounts to 35 per cent, and waste and reusable energy amount to 50 per cent. Improvement of the process *via* tribological approaches may increase the portion of the process-relevant energy to 30 per cent, reducing the destructive energy to 30 per cent and the waste and reusable energy to 40 per cent. Therefore, with the total process-relevant energy staying constant at 15 units (Fig. 3(c)), the destructive energy and the waste and reusable energy are less than half compared to their initial values (20 *versus* 50 units, 15 *versus* 35 units, respectively). An increase of the portion of process-relevant energy has two direct advantages: less damage to the tribosystem and less required energy input. Going green and learning from optimized systems in living nature [**20**] can aid in the step of total energy reduction.

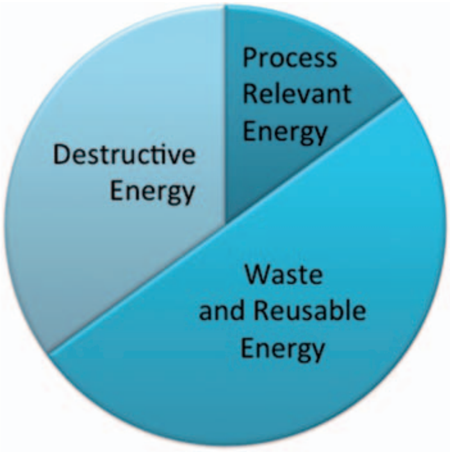

Fig. 2 Energy distribution in a typical tribosystem with room for improvement. The process-relevant energy is just a small portion of the total energy, i.e. destructive and waste and reusable energy have a dominant share

The following four key examples of biological systems are of specific relevance to tribology and have inspired some devices and applications: *Diatoms* [**32–34**] are microscopic algae that have rigid nanostructured surfaces in relative motion; they have evolved self-healing adhesives and interconnected junctions on the nanoscale [**35**]; *white blood cells* exhibiting switchable adhesives on the single-molecule basis [**36**, **37**], *the gecko foot* [**7**] and *articular cartilage* in synovial joints, with friction coefficients reported as low as 0.001 [**38–40**]. More than 100 biological best practices and possible technological applications concerning mechanical wear, shear, tension, buckling, fatigue, fracture (rupture), and deformation and attachment (permanent and temporary) have been identified [**19**].

> *Animals, insects, their internal organs, tissues and biological microstructures and microorganisms experience much the same friction and lubrication forces in their movement as do machines* [**37**].

However, it needs to be mentioned that mere energy optimization is not the primary goal in organisms [**41**] or in constraints in evolution theory [**42**, **43**]. Organisms that are continuously adapting to a variety of environmental conditions and challenges are different to machines as we use them today.

By increasing the process-relevant energy share in a system, even an increase of the destructive energy

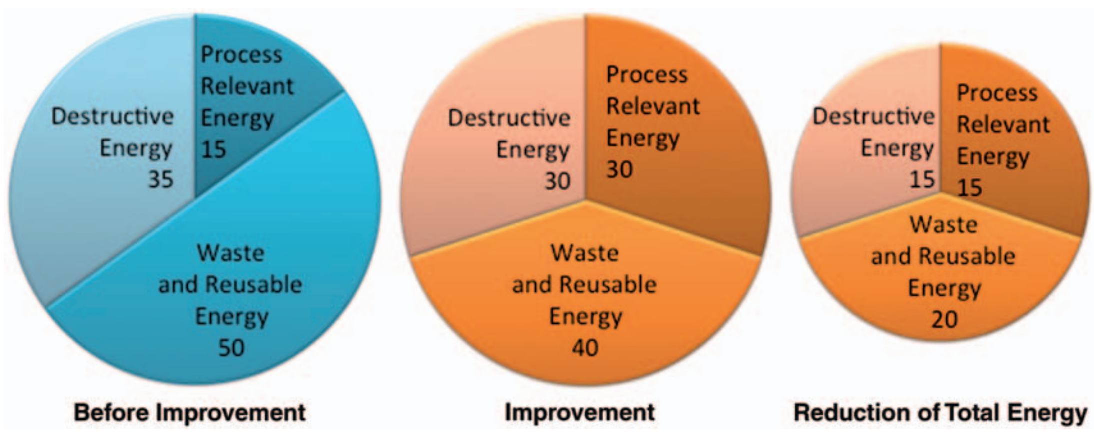

Fig. 3 Tribosystem optimization (estimated values, may vary depending on process). (a) Before improvement. (b) Step 1: improvement of share of process-relevant energy and reduction of non-relevant energy share. (c) Step 2: reduction of total energy required for same output. Note that the destructive energy and the waste and reusable energy portion are less than half compared to the respective values in the initial tribosystem in **Fig. 3**(a)

share can be tolerated if – in relation to the energy needed – the absolute amount of destructive energy in the system is lower than before (equation (1))

$$DE_2 < DE_1 * PE_2/PE_1 \quad (1)$$

with DE_1 being the destructive energy of the old process, DE_2 the destructive energy of the new process, PE_1 the process-relevant energy of the old process, and PE_2 the process-relevant energy of the new process.

3 OPTIMIZATION LEVERS IN NANOTRIBOLOGY

Breaking-in, additives, finishing, and material selection are the four optimization levers in tribology [**44**] (Fig. 4). The technical requirements for successful optimization in tribology comprise aspects related to equipment, cooperation and research (Table 2). From the perspective of green nanotribology, finishing and additives are of key importance. Breaking-in is a process and the relevance of green nanotribology in material selection is translated to finishing and additives.

3.1 Finishing

Nature's materials are complex, multi-functional, hierarchical, and responsive, and in most instances, functionality on the nanoscale is combined with performance on the macroscale [**45**]. Materials engineers have just started to produce nanomaterials with complex surface functionalities and finishings [**46**, **47**]; in nature they have been around for millions of years, e.g. the skeleton of glass sponges or the frustules of diatoms are examples from biology where the complex hierarchical structure rather than the chemical composition of the material determines the outstanding mechanical properties [**35**, **48**, **49**]. Man-made hierarchical nanostructures [**50**, **51**] with tailored surface properties would be one possible approach to address current lubrication issues in MEMS (e.g. superhydrophobicity and low adhesion). Success of developments regarding green nanotribology in this area will depend on our ability to transfer key properties of natural surfaces to the tribosystem.

3.2 Additives

Carrier fluids, such as oil- or water-based lubricants, serve as intermediate layers in macroscopic tribological systems. The additives in these lubricants generally support the macroscopic properties of the carrier fluid, but have no specific functionality on the nanoscale. In nanotribology, the carrier fluid is used as transporter for the additives that provide tribological functionality on the nanoscale. Conventional technological lubricants are uniform chemical compounds achieving specific results regarding the physics of the tribosystem. Biological lubricants are mainly water based, and in many cases the lubricant chemically attaches to the surface (such as in the lubricant layers reported for synovial joints, the lung, or the eye). Current manmade lubricants are mainly oil based. One reason for this is the thermal instability of water-based lubricants at elevated temperatures. One promising area for bioinspired water-based lubricants are ceramic MEMS that work at ambient

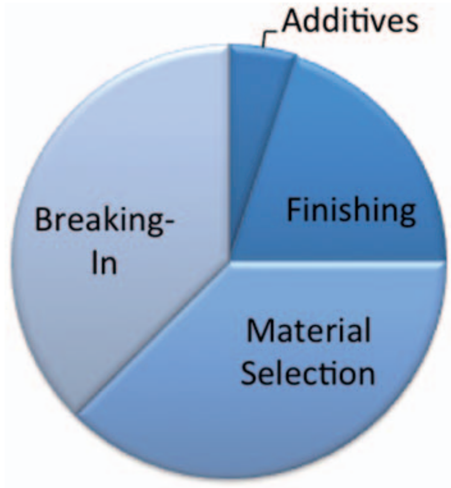

Fig. 4 Optimization levers in tribology. © 2010 M. Scherge, μCT Microtribology Center Karlsruhe. Image reproduced with permission

Table 2. Optimization levers in tribology (translated from Scherge and Rehl [**44**], used with permission)

Optimization lever	Costs	Technical requirements
Breaking-in	Low	Equipment for continuous friction and wear measurement
Material selection	Medium	Cooperation of material and layer developers Scaling (lab → production) Equipment for physical/chemical analysis Equipment for continuous friction and wear measurement
Finishing	Medium	Good cooperation between departments, research → prototyping → production Equipment for continuous friction and wear measurement
Additives	High	Cooperation with additive producers Large portion of basic research Cost intensive equipment Equipment for continuous friction and wear measurement

conditions, with the lubricants chemically attaching to the surface, building monomolecular lubricant layers [**37**].

With decreasing size towards the nanoscale, the physical characteristics of the individual additive particles gain more and more importance. Concerning additives, green nanotribology is mainly concerned with their physical characteristics.

A combination of finishing and additive technology *via* green nanotribology could be the build-up, replenishing, and repair of surface structures by nanoagents.

4 GOALS FOR EFFECTIVE GREEN NANOTRIBOLOGY

The three major goals in green nanotribology are optimized system energy balance, protection of the environment from process residues, and the environmental cost of the process itself (Table 3). Additionally, as an added side issue, nanodiversity needs to be preserved in new streamlined nanoprocesses (Table 3). These goals can be reached *via* well-designed process engineering. For all these three major goals (plus the added side issue) in green nanotribology, biology can serve as a role model (Table 3). Because of space constraints, it is not possible to address all nature's solutions given in Table 3 in detail; therefore, we concentrate here just on some representative ones. Minimizing destructive energy in living nature takes place with water-based lubricants such as the surface active phospholipid layers reported in the lung or in articular cartilage [**2**, **52**], in brushes of charged polymers attached to surfaces rubbing against water-based solutions, as in the surface of the eye when blinking [**53**] or in snail slime, a substance that is both a lubricant and an adhesive (many snails can move upside-down on a glass plate) [**54**]. Instructive examples for the use of structures rather than materials are structural colours in butterfly or beetle wings; they are multifunctional surfaces contributing, e.g. to coloration, hydrophobic and cleaning self-cleaning effects as well as wear resistance [**55**]. Biological examples for Nachtigall's general principles that can be applied by tribologists who are not at all involved in biology comprise (as an example for integration instead of additive construction and multifunctionality instead of monofunctionality) multifunctional biological

Table 3 Major goals for effective green nanotribology and how it can benefit from biology

Green nanotribology	Major goals	Importance	Nature's solutions
Optimized system energy balance	Minimizing destructive energy	Medium	Water-based lubricants Predetermined breaking points Responsive materials Structure rather than material
	Shield tribosystem against damaging consequences	High	Integration instead of additive construction [**20**] Optimization of the whole instead of maximization of a single component feature [**20**] Multi-functionality instead of mono-functionality [**20**] Energy efficiency [**20**] Development *via* trial-and-error processes [**20**]
	Reuse energy and neutralize waste energy	Low	Organisms
Protection of the environment from process residues	Unused agents	Low	Reuse in the ecosystem
	Pollutants	Medium	Biodegradability Confined spaces for chemical processes
	Process reliability and worst case scenario dangers	High	Highly developed over time (evolution)
Environmental cost of the process itself	Effort to produce agents	High	Optimized (on systems level)
	Purer inputs with more waste in the preparation	Medium	Water-based chemistry Cell organelles serve as nanofactories Shielding of process *via* membranes
	Different economy of scale	Low	Major evolutionary transitions Mammals *versus* cold-blooded animals
Preservation of nanodiversity		Unknown	Additives in ultra-low concentration ensure nanodiversity Reuse of the same base material with slight modifications for various applications

surfaces such as the surface of a moth eye that exhibit nanostructures, which provide anti-reflective coating properties by gradual change in the refractive index, and furthermore self-cleaning and anti-wetting properties [**56**] (see [**57**] for technological application), nanostructured, hierarchical silica frustules of micrometer-small diatoms as an example for optimization of the whole instead of maximization of a single-component feature [**32**] and stick-slip processes in protein dynamics [**37**] as an example for energy efficiency. Biological examples for the reuse of energy and the neutralization of waste energy as well as for the protection of the environment from process residues such as unused agents is reuse in the ecosystem, e.g. in dung beetles on the species level and in the food chain on the systems level. Biological examples concerning protection of the environment from pollutants are the biodegradability of complex biochemical substances that disintegrate into simpler, less poisonous substances or cell organelles as examples for confined spaces where chemical processes take place [**58**]. Also, current life itself – complex, interdependent and interconnected – is the best example for process reliability and safeguarding against worst scenario dangers.

One possible way to get inspiration from biology is to apply the Biomimicry Innovation Method (BIM) [**59**]. BIM is a successful method in biomimetics. Biomimicry is an innovation method that seeks sustainable solutions by emulating nature's time-tested patterns and strategies; therefore, it is an applicable method to receive inspiration from nature in green nanotribology. The goal of BIM is to create products, processes, and policies – new ways of living – that are well adapted to life on earth over the long haul. This method has been extensively applied to identify biological systems, processes, and materials that can inspire tribology [**19**, **60–63**].

The steps in BIM are as follows [**59**]: identify function [**64**, **65**], biologize the question, find nature's best practices, and generate product ideas.

Identify function: The biologists distil challenges posed by engineers/natural scientists/architects and/or designers to their functional essence.

Biologize the question: In the next step, these functions are translated into biological questions such as 'How does nature manage lubrication?' or 'How does nature bond parts together?' The basic question is 'What would nature do here?'

Find nature's best practices: Scientific databases as well as living nature itself are used to obtain a compendium of how plants, animals, and ecosystems solve the specific challenge.

Generate process/product ideas: From these best practices, ideas for cost-effective, innovative, life-friendly, and sustainable products and processes are generated.

Promising points to address with green nanotribology, possibly with the help of the BIM, appear at various places in a tribosystem (see Fig. 5 for generalized tribosystem). In their classic book *Biological Micro-*

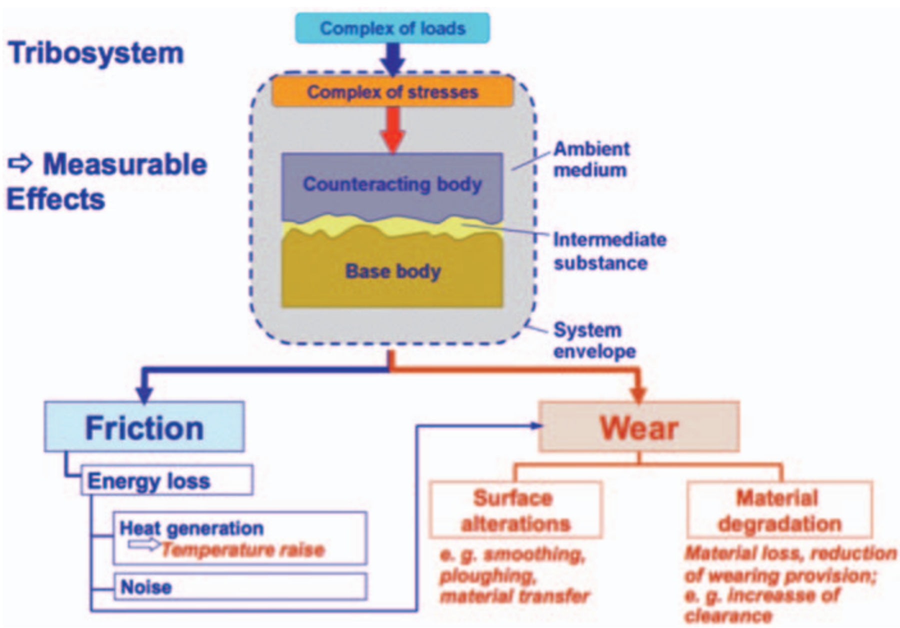

Fig. 5 Generalized tribosystem. © 2008, F. Franek, Austrian Center of Competence for Tribology. Image reproduced with permission

and Nanotribology: Nature's Solutions, Scherge and Gorb [**66**], for example, provide information about friction, adhesion, and wear of biological systems and application of this new knowledge to the design of MEMS, the development of new types of monolayer lubrication, the invention of new adhesives or the construction of artificial joints, drawing biological inspiration, e.g. from joints and articular cartilage regarding systems with reduced friction, bird feather interlocking devices and friction in fish spines regarding systems with increased friction, and sticking in tree frogs, adhesion in bats, and frictional devices of insects (attachment pads of flies) regarding systems with increased adhesion [**66**].

Energy and wear management in biology can give valuable inspiration concerning tackling energy loss *via* heat generation and noise (such as in the case of stochastic resonance in biological systems [**67**]), as well as wear induced by surface alterations and material degradation (see the literature on friction and wear in synovial joints). Self-healing is a basic property in various biological materials: skin and bones are well-known examples. Current technology has just started to learn from nature how to produce such exquisitely engineered materials [**13**, **68**]. Self-healing modular adhesives produced by microscopic algae [**69**] might, e.g. aid in the development of novel under-water adhesives, and the self-healing properties of skin can inspire novel materials such as self-repairing anti-corrosion coatings [**70–73**].

Three questions need to be addressed for the assessment of the most harmful form of energy:

1. Do the processes get greener with the envisaged nanotribology (e.g. better coatings, less wear – in the case of nanotribology also stiction is a major issue)?
2. Do the processes turn worse because of chemical reactions?
3. Is the envisaged green nanotribology only pseudo-green, and in reality, the negative impact on the environment/biology is only translated to other layers?

The usage of new technologies, materials and devices, might increase advantages, but generate new problems (technology assessment) [**74**]. Exact eco-balance calculations need to be performed to prevent pseudo-green approaches. Biodiesel, for example, might be greener in the production than conventional products, yet has still major unresolved technical (including tribological) concerns when used at concentrations greater than 5 per cent [**75**]. Biodiesel is hygroscopic, i.e. attracts water from the surrounding environment through either absorption or adsorption – and this water in the fuel induces microbiological activity, corrosion, and fuel instability.

5 SUMMARY, CONCLUSIONS, AND OUTLOOK

There are three uses of green nanotribology regarding process performance: to accelerate the process by achieving the goals for effective green nanotribology, to save energy by improving the energy balance in tribosystems, and to strengthen the tribosystem along the optimization levers.

The key issue in green nanotribology is to achieve an increase in the amount of process-relevant energy, and to reduce the harmful consequences by a proper application of nanotechnology. Green nanotribology focuses on sustainable solutions; in lubrication, for example, ultimately, not the perfect lubricant counts, but the development/usage of finished surfaces that do not need lubricants at all.

A smart combination of mechanical, energetic, and chemical approaches, combined with optimally designed materials, and minimized stresses to the environment and biology, paves the way towards green nanotribology. Here, again, one can look for inspiration in living nature. Most of the issues mentioned in the tribological triangle in Fig. 6 have already been addressed by biological systems: Scherge and Gorb [**66**] list biological systems, such as joints and articular cartilage, muscle connective tissues, fish, primate skin, snake scales, bird feathers, molluscs, barnacles, starfish, insects and spiders, crustaceans, and tree frogs, concerning attachment, increased or reduced friction, and adhesion, respectively, and frictional devices of insects; Gebeshuber *et al.* [**19**] list best-practice materials, structures, and processes in organisms regarding wear, shear, tension, buckling, fatigue, fracture (rupture), deformation, and permanent or temporal adhesion. Some of the examples they give are lubrication of chameleon tongues [**76**], self-sharpening teeth in the American beaver and in sea urchins [**77**, **78**], wood as a classical example of a natural reinforced material [**79**], bird bones as examples for lightweight yet strong materials [**80**], Stefan adhesion, which occurs when a thin layer of viscous fluid separates two surfaces, as it occurs in various organisms when they temporarily resist shearing loads [**81**], auxetic membranes that get thicker when stretched [**82**], and nature's strongest adhesive, the underwater glue of an aquatic bacterium [**83**].

The questions in this respect are to which degree we need to replenish agents, which share of them is actually used in the process and how much is wasted; and, what effects do altered and mutated agents have on the system and the environment? It should also be known how fast the function of nanostructured

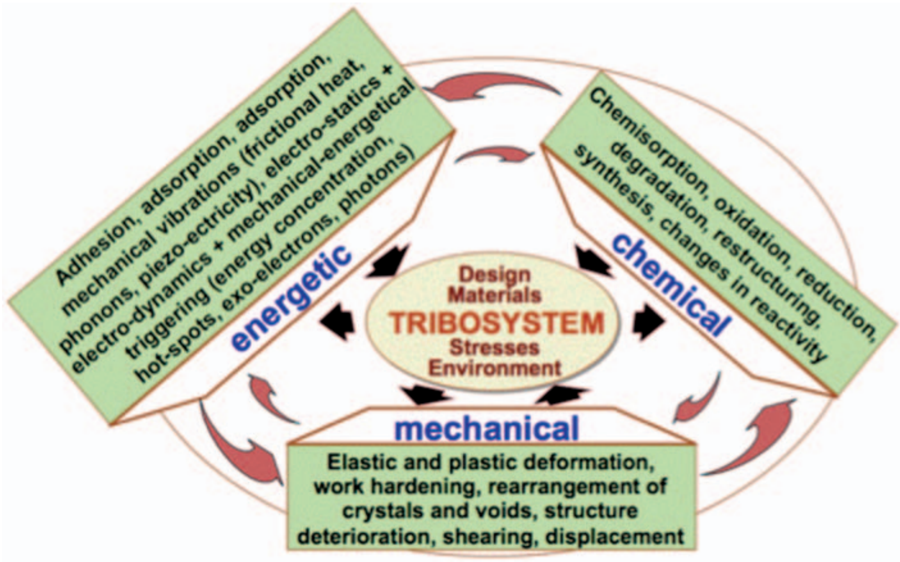

Fig. 6 Effects and their causes in a tribological system – the tribological triangle. © F. Franek, Austrian Center of Competence for Tribology, using the tribological triangle concept from H. Faigle, Faigle Kunststoffe, Austria. http://www.faigle.com. Image reproduced with permission

surfaces/materials wears off and to which degree specific functions lose their effects with time; and, is a suboptimal nano-solution still a good solution? A final question is the control – nanotechnology means that the relatively huge volume of the 'process system' is subdivided into a vast number of nanospaces with individual reactions with a differing number of process materials and agents – it is not clear if all these processes function as they should. A change in the balance of materials and nanoagents causes differing reactions and results – which contributes to the basic difference between tribology and nanotribology.

Now, it is our task to transfer this knowledge to develop true green nanotribology, for the benefit of all. One way to go is to actively try to bridge the gaps between biotribological systems, inventors, innovators and investors, to have a pipeline from knowledge *via* prototypes to products, *via* biomimetic approaches [**21**]. A huge body of knowledge is already published in biology papers – this now needs to be made accessible for tribologists and used in further research and development. New ways of scientific publishing and accessing human knowledge inspired by bionanotribological approaches might help tackle this problem [**84**].

This article establishes a definition of green nanotribology. With its low environmental impact and its capability to improve triboprocesses on a large economic scale, green nanotribology has the potential to specifically address issues that arise due to global challenges [**85**] regarding energy as well as science and technology [**86**].

ACKNOWLEDGEMENTS

The National University of Malaysia funded part of this study with its leading-edge research project scheme 'Arus Perdana' (UKM-AP-NBT-16-2010) and the Austrian Society for the Advancement of Plant Sciences funded part of this study *via* the Biomimetics Pilot Project 'BioScreen'. F. Aumayr, H. Störi, and G. Badurek (Vienna University of Technology) are acknowledged for enabling ICG years of research in the inspiring environment in Malaysia.

FUNDING

This work was supported by the UKM leading-edge research project scheme 'Arus Perdana' [grant number UKM-AP-NBT-16-2010].

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