INTRODUCTION

Green tribology: principles, research areas and challenges

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In this introductory paper for the Theme Issue on green tribology, we discuss the concept of green tribology and its relation to other areas of tribology as well as other ‘green’ disciplines, namely, green engineering and green chemistry. We formulate the 12 principles of green tribology: the minimization of (i) friction and (ii) wear, (iii) the reduction or complete elimination of lubrication, including self-lubrication, (iv) natural and (v) biodegradable lubrication, (vi) using sustainable chemistry and engineering principles, (vii) biomimetic approaches, (viii) surface texturing, (ix) environmental implications of coatings, (x) real-time monitoring, (xi) design for degradation, and (xii) sustainable energy applications. We further define three areas of green tribology: (i) biomimetics for tribological applications, (ii) environment-friendly lubrication, and (iii) the tribology of renewable-energy application. The integration of these areas remains a primary challenge for this novel area of research. We also discuss the challenges of green tribology and future directions of research.

Keywords: tribology; alternative energy; nanotechnology; biomimetics

1. Introduction

Tribology (from the Greek word τριβόω ‘tribo’ meaning ‘to rub’) is defined by the Oxford dictionary as ‘the branch of science and technology concerned with interacting surfaces in relative motion and with associated matters (as friction, wear, lubrication and the design of bearings)’ (Oxford English Dictionary; http://grove.ufl.edu/~wgsawyer/). The term was introduced and defined for the first time in 1966 by Prof. H. Peter Jost, then the chairman of a working group of lubrication engineers, in his published report for the UK Department of Education and Science (Jost 1966). It was reported that huge sums of money have been lost

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One contribution of 11 to a Theme Issue ‘Green tribology’.
in the UK annually owing to the consequences of friction, wear and corrosion. As a result, several centres for tribology were created in many countries. Since then, the term has diffused into the international engineering field, and many specialists now claim to be tribologists.

Typical tribological studies cover friction, wear, lubrication and adhesion, and involve the efforts of mechanical engineers, material scientists, chemists and physicists (Bhushan 1999, 2001, 2002). Since the emergence of the word tribology almost 50 years ago, many new areas of tribological studies have developed that are at the interface of various scientific disciplines, and various aspects of interacting surfaces in relative motion have been the focus of tribology. These areas include, for example, nanotribology, biotribology, the tribology of magnetic storage devices and microelectromechanical systems (MEMS)/nanoelectromechanical systems and adhesive contact (Bhushan & Gupta 1991; Bhushan 1996, 1999, 2000, 2001, 2002, 2008, 2010). The research in these areas is driven mostly by the advent of new technologies and new experimental techniques for surface characterization.

Recently, the new concept of ‘green tribology’ has been defined as ‘the science and technology of the tribological aspects of ecological balance and of environmental and biological impacts’. H. P. Jost (2009, unpublished data) elaborated on the need for green tribology and has mentioned that ‘the influence of economic, market and financial triumphalisms have retarded tribology and could retard “green tribology” from being accepted as a not-unimportant factor in its field… Therefore, by highlighting the economic benefits of tribology, tribology societies, groups and committees are likely to have a far greater impact on the makers of policies and the providers of funding than by only preaching the scientific logic… Tribology societies should highlight to the utmost the economic advantage of tribology. It is the language financial oriented policy makers and markets, as well as governments, understand’.

The specific field of green or environment-friendly tribology emphasizes the aspects of interacting surfaces in relative motion, which are of importance for energy or environmental sustainability or which have impact upon today’s environment. This includes tribological technology that mimics living nature (biomimetic surfaces) and thus is expected to be environment friendly, the control of friction and wear, which is of importance for energy conservation and conversion, environmental aspects of lubrication and surface-modification techniques and tribological aspects of green applications, such as wind-power turbines, tidal turbines or solar panels (figure 1). It is clear that a number of tribological problems could be put under the umbrella of green tribology and are of mutual benefit to one another.

Green tribology can be viewed in the broader context of two other ‘green’ areas: green engineering and green chemistry. The US Environmental Protection Agency defines green engineering as ‘the design, commercialization and use of processes and products that are technically and economically feasible while minimizing (i) generation of pollution at the source and (ii) risk to human health and the environment’ (US Environmental Protection Agency 2010). The three tiers of green engineering assessment in design involve: (i) process research and development, (ii) conceptual/preliminary design, and (iii) detailed design pollution prevention, process heat/energy integration and process mass integration (Allen & Shonnard 2001).
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Another related area is green chemistry, also known as sustainable chemistry, which is defined as the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances (US Environmental Protection Agency 2010). Green chemistry technologies provide a number of benefits, including reduced waste, eliminating costly end-of-the-pipe treatments, safer products, reduced use of energy and resources and improved competitiveness of chemical manufacturers and their customers. Green chemistry consists of chemicals and chemical processes designed to reduce or eliminate negative environmental impacts. The use and production of these chemicals may involve reduced waste products, non-toxic components and improved efficiency. Anastas & Warner (1998) formulated the 12 principles of green chemistry that provided a road map for chemists to implement green chemistry:

1. Prevention of waste is better than cleaning up.
2. Maximum incorporation into the final product of all materials used in the process.
3. Chemical synthesis should incorporate less hazardous or toxic materials, when possible.
4. Chemical products should be designed to reduce toxicity.
5. Auxiliary substances, such as solvents, should be safe whenever used.
6. Energy efficiency requirements should be recognized. Synthetic methods should be conducted at ambient temperature and pressure, whenever possible.
7. A raw material or feedstock should be renewable, whenever possible.
8. Reduce unnecessary derivatives.
9. Catalytic reagents are superior to stoichiometric reagents.
10. Chemical products should be degradable at the end of their function.
11. Real-time analysis, monitoring and control should be implemented to prevent the formation of hazardous substances.
12. Substances and their use in the chemical process should be chosen to minimize the risk of accidents and prevent fires, explosions, spills, etc.

A number of green chemistry metrics have been suggested to quantify the environmental efficiency of a chemical process. These metrics include the environmental factor (‘E-factor’), which is equal to the total mass of waste divided
by the mass of product (Sheldon 1992), the atom economy (Trost 1991), the effective mass yield (Hudlicky et al. 1999), the carbon efficiency and reaction mass efficiency (Constable et al. 2001), etc.

Since tribology is an interdisciplinary area that involves, among other fields, chemical engineering and materials science, the principles of green chemistry are applicable to green tribology as well. However, since tribology involves, besides the chemistry of surfaces, other aspects related to the mechanics and physics of surfaces, there is a need to modify these principles. The principles of green tribology will be formulated in the following section.

2. Twelve principles of green tribology

Below, we formulate the principles of green tribology, which belong to the three areas, suggested in the preceding section. Some principles are related to the design and manufacturing of tribological applications (iii–x), while others belong to their operation (i, ii, xi and xii). We followed tradition and limited the number of principles to twelve.

(i) Minimization of heat and energy dissipation. Friction is the primary source of energy dissipation. According to some estimates, about one-third of the energy consumption in the USA is spent to overcome friction. Most energy dissipated by friction is converted into heat and leads to the heat pollution of atmosphere and the environment. The control of friction and friction minimization, which leads to both energy conservation and prevention of damage to the environment owing to heat pollution, is a primary task of tribology. It is recognized that for certain tribological applications (e.g. car brakes and clutches), high friction is required; however, ways of effective use of energy for these applications should be sought as well.

(ii) Minimization of wear is the second most important task of tribology that has relevance to green tribology. In most industrial applications, wear is undesirable. It limits the lifetime of components and therefore creates the problem of their recycling. Wear can lead also to catastrophic failure. In addition, wear creates debris and particles that contaminate the environment and can be hazardous for humans in certain situations. For example, wear debris generated after human joint-replacement surgery is the primary source of long-term complications in patients.

(iii) Reduction or complete elimination of lubrication and self-lubrication. Lubrication is a focus of tribology since it leads to the reduction of friction and wear. However, lubrication can also lead to environmental hazards. It is desirable to reduce lubrication or achieve the self-lubricating regime, when no external supply of lubrication is required. Tribological systems in living nature often operate in the self-lubricating regime. For example, joints form essentially a closed self-sustainable system.

(iv) Natural lubrication (e.g. vegetable-oil-based) should be used in cases when possible, since it is usually environmentally friendly.

(v) Biodegradable lubrication should also be used when possible to avoid environmental contamination.

(vi) Sustainable chemistry and green engineering principles should be used for the manufacturing of new components for tribological applications, coatings and lubricants.
(vii) **Biomimetic approaches** should be used whenever possible. These include biomimetic surfaces, materials and other biomimetic and bioinspired approaches, since they tend to be more ecologically friendly.

(viii) **Surface texturing** should be applied to control surface properties. Conventional engineered surfaces have random roughness, and the randomness is the factor that makes it extremely difficult to overcome friction and wear. On the other hand, many biological functional surfaces have complex structures with hierarchical roughness, which defines their properties. Surface texturing provides a way to control many surface properties relevant to making tribo-systems more ecologically friendly.

(ix) **Environmental implications of coatings** and other methods of surface modification (texturing, depositions, etc.) should be investigated and taken into consideration.

(x) **Design for degradation** of surfaces, coatings and tribological components. Similar to green chemistry applications, the ultimate degradation/utilization should be taken into consideration during design.

(xi) **Real-time monitoring**, analysis and control of tribological systems during their operation should be implemented to prevent the formation of hazardous substances.

(xii) **Sustainable energy applications** should become the priority of the tribological design as well as engineering design in general.

3. **Areas of green tribology**

The following three focus areas of tribology have the greatest impact on environmental issues, and, therefore, they are of importance for green tribology: (i) biomimetic and self-lubricating materials/surfaces, (ii) biodegradable and environment-friendly lubricants, and (iii) tribology of renewable and/or sustainable sources of energy. Below, we briefly discuss the current state of these areas and their relevance for the novel field of green tribology.

(a) **Biomimetic surfaces**

Biomimetics (also referred to as bionics or biomimicry) is the application of biological methods and systems found in nature to the study and design of engineering systems and modern technology. It is estimated that the 100 largest biomimetic products generated approximately US $1.5 billion over the years 2005–2008. The annual sales are expected to continue to increase dramatically (Bhushan 2009). Many biological materials have remarkable properties that can hardly be achieved by conventional engineering methods. For example, a spider can produce huge amounts (comparing with the linear size of his body) of silk fibre, which is stronger than steel, without any access to the high temperatures and pressures that would be required to produce such materials as steel using conventional human technology. These properties of biomimetic materials are achieved owing to their composite structure and hierarchical multi-scale organization (Fratzl & Weinkamer 2007). The hierarchical organization provides biological systems with the flexibility needed to adapt to the changing environment. As opposed to the traditional engineering approach, biological materials are grown without the final design specifications, but by using the
recipes and recursive algorithms contained in their genetic code. The difference of natural versus engineering design is the difference of growth versus fabrication (Fratzl 2007; Nosonovsky & Bhushan 2008, 2009a). Hierarchical organization and the ability of biological systems to grow and adapt also provide a natural mechanism for the repair or healing of minor damage in the material.

The remarkable properties of the biological materials serve as a source of inspiration for materials scientists and engineers, indicating that such performance can be achieved if the paradigm of materials design is changed. While, in most cases, it is not possible to directly borrow solutions from living nature and to apply them in engineering, it is often possible to take biological systems as a starting point and a source of inspiration for engineering design. Molecular-scale devices, superhydrophobicity, self-cleaning, drag reduction in fluid flow, energy conversion and conservation, high adhesion, reversible adhesion, aerodynamic lift, materials and fibres with high mechanical strength, biological self-assembly, antireflection, structural coloration, thermal insulation, self-healing and sensory-aid mechanisms are some of the examples found in nature that are of commercial interest.

Biomimetic materials are also usually environmentally friendly in a natural way, since they are a natural part of the ecosystem. For this reason, the biomimetic approach in tribology is particularly promising. In the area of biomimetic surfaces, a number of ideas have been suggested (Scherge & Gorb 2001; Bar-Cohen 2006; Gorb 2006; Nosonovsky & Bhushan 2008; Favret & Fuentes 2009).

(i) The Lotus-effect-based non-adhesive surfaces. The term ‘Lotus effect’ stands for surface-roughness-induced superhydrophobicity and self-cleaning. Superhydrophobicity is defined as the ability to have a large (more than 150°) water contact angle and, at the same time, low contact angle hysteresis. The lotus flower is famous for its ability to emerge clean from dirty water and to repel water from its leaves. This is due to a special structure of the leaf surface (multi-scale roughness) combined with hydrophobic coatings (figure 2) (Nosonovsky & Bhushan 2007a, b). These surfaces have been fabricated in the laboratory with comparable performance (Bhushan et al. 2009).

Adhesion is a general term for several types of attractive forces that act between solid surfaces, including the van der Waals force, electrostatic force, chemical bonding and the capillary force, owing to the condensation of water at the surface. Adhesion is a relatively short-range force, and its effect (which is often undesirable) is significant for microsystems that have contacting surfaces. The adhesion force strongly affects friction, mechanical contact and tribological performance of such system surfaces, leading, for example, to ‘stiction’ (combination of adhesion and static friction; Bhushan 1996, 2008), which precludes microelectromechanical switches and actuators from proper functioning. It is therefore desirable to produce non-adhesive surfaces, and applying surface microstructure mimicking the Lotus effect (as well as its modifications, e.g. the so-called ‘petal effect’; figure 3) has been successfully used for the design of non-adhesive surfaces, which are important for many tribological applications.

(ii) The Gecko effect, which stands for the ability of specially structured hierarchical surfaces to exhibit controlled adhesion. Geckos are known for their ability to climb vertical walls owing to a strong adhesion between their toes and
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Figure 2. (a) Scanning electron microscope (SEM) micrographs (shown at three magnifications) of lotus (*Nelumbo nucifera*) leaf surface, which consists of microstructure formed by papillose epidermal cells covered with epicuticular wax tubules on the surface, which create nanostructure and (b) image of a water droplet sitting on the lotus leaf (Bhushan *et al.* 2009). Scale bars, (a)(i) 10 μm, (ii) 2 μm and (iii) 0.4 μm.

Figure 3. Optical micrographs of water droplets on Rosa cv. Bairage at (a) 0° and (b) 180° tilt angles. A droplet is still suspended when the petal is turned upside down (Bhushan & Her 2010). Scale bars, (a,b) 500 μm.

... a number of various surfaces. They can also detach easily from a surface when needed (figure 4). This is due to a complex hierarchical structure of gecko foot surface. The Gecko effect is used for applications when strong adhesion is needed (e.g. adhesive tapes). The Gecko effect can be combined with the self-cleaning abilities (Bhushan 2007; Nosonovsky & Bhushan 2008).

(iii) Microstructured surfaces for underwater applications, including easy flow owing to boundary slip, the suppression of turbulence (the shark-skin effect; figure 5) and antibiofouling (the fish-scale effect). Biofouling and biofilming are the undesirable accumulation of micro-organisms, plants and algae on structures that are immersed in water. Conventional antifouling coatings for ship hulls are
Figure 4. The Tokay gecko has the ability to climb walls and detach from surfaces easily at will.

Figure 5. Scale structure on a Galapagos shark (*Carcharhinus galapagensis*; Reif 1985). Scale bar, 0.5 mm.
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often toxic and environmentally hazardous. On the other hand, in living nature, there are ecological coatings (e.g. fish scale), so a biomimetic approach is sought (Chambers et al. 2006; Genzer & Efimenko 2006; Nosonovsky & Bhushan 2009b; Dean & Bhushan 2010; Jung & Bhushan 2010).

(iv) Oleophobic surfaces capable of repelling organic liquids. The principle can be similar to superhydrophobicity, but it is much more difficult to produce an oleophobic surface because surface energies of organic liquids are low, and they tend to wet most surfaces (Nosonovsky 2007; Tuteja et al. 2007, 2008; Nosonovsky & Bhushan 2009b). Underwater oleophobicity can also be used to design self-cleaning and antifouling surfaces (figure 6; Jung & Bhushan 2009).

(v) Microstructured surfaces for various optical applications, including non-reflective (the Moth-eye effect), highly reflective, coloured (in some cases, including the ability to dynamically control coloration) and transparent surfaces. Optical surfaces are sensitive to contamination, so the self-cleaning ability should often be combined with optical properties (Nosonovsky & Bhushan 2008; Gombert & Blasi 2009).

(vi) Microtextured surfaces for de-icing and anti-icing (figure 7). De-icing (the removal of frozen contaminant from a surface) and anti-icing (protecting against the formation of frozen contaminant) are significant problems for many applications that have to operate below the water-freezing temperature: aircrafts, machinery, road and runway pavements, traffic signs and traffic lights, etc. The traditional approaches to de-icing include mechanical methods, heating and the deposition of dry or liquid chemicals that lower the freezing point of water. Anti-icing is accomplished by applying a protective layer of a viscous anti-ice fluid. All anti-ice fluids offer only limited protection, dependent upon frozen-contaminant type and precipitation rate, and they fail when they no longer can absorb the contaminant. In addition to limited efficiency, these de-icing fluids, such as propylene glycol or ethylene glycol, can be toxic and raise environmental concerns. Anti-icing on roadways is used to prevent ice and snow from adhering to the pavement, allowing easier removal by mechanical methods.

Ice formation occurs owing to condensation of vapour-phase water and further freezing of liquid water. For example, droplets of supercooled water that exist in stratiform and cumulus clouds crystallize into ice when they are struck by the wings of passing airplanes. Ice formation on other surfaces, such as pavements or traffic signs, also occurs via the liquid phase. It is therefore suggested that a water-repellent surface can also have de-icing properties (Cao et al. 2009). When a superhydrophobic surface is wetted by water, an air layer or air pockets are usually kept between the solid and the water droplets. After freezing, ice will not adhere to the solid owing to the presence of air pockets and will be easily washed or blown away.

(vii) MEMS-based dynamically tunable surfaces for the control of liquid/matter flow and/or coloration (for example, mimicking the coloration control in cephalopods), used for displays and other applications, the so-called ‘origami’ (Sidorenko et al. 2007; Bucaro et al. 2009).

(viii) Various biomimetic microtextured surfaces to control friction, wear and lubrication (Varenberg & Gorb 2009; Bhushan 2010).

(ix) Self-lubricating surfaces, using various principles, including the ability for friction-induced self-organization (Nosonovsky & Bhushan 2009c).
Figure 6. (a) Schematics of a solid–water–oil interface system. A specimen is first immersed in water, and then an oil droplet is gently deposited using a microsyringe, and the static contact angle is measured. (b) Optical micrographs of droplets at three different phase interfaces on a micropatterned surface (shark-skin replica): (i) without and (ii) with C$_{20}$F$_{42}$ (Jung & Bhushan 2009). Scale bar, (b) 0.5 mm.

(x) Self-repairing surfaces and materials, which are able to heal minor damage (cracks, voids; Nosonovsky & Bhushan 2009c, 2010).

(xi) Various surfaces with alternate (and dynamically controlled) wetting properties for micro-/nanofluidic applications, including the Darkling beetle effect, e.g. the ability of a desert beetle to collect water on its back using the
Figure 7. The principle of applying of surface microstructure for de-icing.

Figure 8. The water-capturing surface of the fused overwings (elytra) of the desert beetle *Stenocara* sp. (a) Adult female, dorsal view; peaks and valleys are evident on the surface of the elytra and (b) SEM image of the textured surface of the depressed areas (Parker & Lawrence 2001). Scale bars, (a) 10 mm and (b) 10 μm.

hydrophilic spots on an otherwise hydrophobic surface of its back (Parker & Lawrence 2001; Rechenberg & El Khyeri 2007; Nosonovskiy & Bhushan 2008) (figure 8).

(xii) Water-strider effect mimicking the ability of insects to walk on water using the capillary forces. The hierarchical organization of the water-strider leg surface plays a role in its ability to remain dry on the water surface (figure 9; Gao & Jiang 2004).

(xiii) The ‘sand fish’ lizard effect, able to dive and ‘swim’ in loose sand owing to special electromechanical properties of its scale (Rechenberg & El Khyeri 2007; Nosonovskiy & Bhushan 2008).

Environmental engineers have only just started paying attention to biomimetic surfaces. Raibeck *et al.* (2009) investigated the potential environmental benefits and burdens associated with using the Lotus-effect-based self-cleaning surfaces. They found that while the use-phase benefits are apparent, production burdens can outweigh them when compared with other cleaning methods,
so a more thoughtful and deliberate use of bioinspiration in sustainable engineering is needed. Clearly, more studies are likely to emerge in the near future.

(b) Biodegradable lubrication

In the area of environment-friendly and biodegradable lubrication, several ideas have been suggested:

— The use of natural (e.g. vegetable-oil-based or animal-fat-based) biodegradable lubricants. This involves oils that are used for engines, hydraulic applications and metal-cutting applications. In particular, corn, soybean and coconut oils have been used so far (the latter is of particular interest in tropical countries such as India). These lubricants are potentially biodegradable, although in some cases, chemical modification or additives for best performance are required. Vegetable oils can have excellent lubricity, far superior than that of mineral oil. In addition, they have a very high viscosity index and high flash/fire points. However, natural oils often lack sufficient oxidative stability, which means that the oil will oxidize rather quickly during use, becoming thick and polymerizing to a plastic-like consistency. Chemical modification of vegetable oils and/or the use of antioxidants can address this problem (table 1; Mannekote & Kailas 2009).
Table 1. The content of CO and CO2 in exhaust gas lubricated with regular and vegetable oil (Mannekote & Kailas 2009).

<table>
<thead>
<tr>
<th>sample</th>
<th>CO2 (%)</th>
<th>CO (%)</th>
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<tbody>
<tr>
<td>engine oil</td>
<td>4.5</td>
<td>0.92</td>
</tr>
<tr>
<td>coconut oil</td>
<td>2.9</td>
<td>0.67</td>
</tr>
<tr>
<td>palm oil</td>
<td>3.4</td>
<td>0.73</td>
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</table>

— Powder lubricants and, in particular, boric acid lubricants. In general, these tend to be much more ecologically friendly than the traditional liquid lubricants (Kabir et al. 2008). Boric acid and MoS2 powder can also be used as an additive to the natural oil. Friction and wear experiments show that the nanoscale (20 nm) particle boric acid additive lubricants significantly outperformed all of the other lubricants with respect to frictional and wear performance. In fact, the nanoscale boric acid powder-based lubricants exhibited a wear rate more than an order of magnitude lower than the MoS2 and larger sized boric acid additive-based lubricants (M. R. Lovell, M. A. Kabir, P. L. Menezes & C. F. Higgs 2010, personal communication).
— Self-replenishing lubrication that uses oil-free environmentally benign powders for lubrication of critical components such as bearings used in fuel cell compressors and expanders (Wornyoh et al. 2007).

(c) Renewable energy

The tribology of renewable sources of energy is a relatively new field of tribology. Today, there are meetings and sections devoted to the tribology of wind turbines at almost every tribology conference, and they cover certain issues specific for these applications. Unlike in the case of the biomimetic approach and environment-friendly lubrication, it is not the manufacturing or operation, but the very application of the tribological system that involves green issues, namely, environmentally friendly energy production. The following issues can be mentioned.

(i) Wind-power turbines have a number of specific problems related to their tribology, and constitute a well-established area of tribological research. These issues include water contamination, electric arcing on generator bearings, issues related to the wear of the mainshaft and gearbox bearings and gears, the erosion of blades (solid particles, cavitation, rain, hail stones), etc. (Kotzalas & Lucas 2007).
(ii) Tidal-power turbines are another important way of producing renewable energy, which involves certain tribiological problems. Tidal-power turbines are especially popular in Europe (particularly, in the UK), which remains the leader in this area, although several potential sites in North America have been suggested. There are several specific tribological issues related to the tidal-power turbines, such as their lubrication (seawater, oils and greases), erosion, corrosion and biofouling, as well as the interaction between these modes of damage (Batten et al. 2008).
Besides tidal, the ocean-water flow energy and river flow energy (without dams) can be used with the application of special turbines, such as the Gorlov helical turbine (figure 10; Gorban’ et al. 2001), which provides the same direction of rotation independent of the direction of the current flow. These applications also involve specific tribological issues.

(iii) Geothermal energy plants are used in the USA (in particular, at the Pacific coast and Alaska); however, their use is limited to the geographical areas at the edges of tectonic plates (Rybach 2007). In 2007, they produced 2.7 GW of energy in the USA, with Philippines (2.0 GW) and Indonesia (1.0 GW) in second and third places (Bertani 2007). There are several issues related to the tribology of geothermal energy sources that are discussed in the literature.

4. Challenges

In the preceding sections, we have outlined the need for green tribology, its principles and primary areas of research. As a new field, green tribology has a number of challenges. One apparent challenge is the development of the above-mentioned fields in such a manner that they could benefit from each other. Only in the case where such a synthesis is performed is it possible to see green tribology as a coherent and self-sustained field of science and technology,
rather than a collection of several topics of research in tribology and surface engineering. There is apparently potential synergy in the use of the biomimetic approach, microstructuring, biodegradable lubrication, self-lubrication and other novel approaches, as well as in developing methods of their applications to sustainable engineering and energy production. Clearly, more research should be done for the integration of these fields. Some ideas could be borrowed from the related field of green chemistry, for example, developing quantitative metrics to assess the environmental impact of tribological technologies.

Green tribology should be integrated into world science and make its impact on the solutions for worldwide problems, such as the change of climate and the shortage of food and drinking water. H. P. Jost (2009, unpublished data) mentioned the economical potential of the new discipline: ‘The application of tribological principles alone will, of course, not solve these world-wide problems. Only major scientific achievements are likely to be the key to their solution, of which I rate energy as one of the most important ones. For such tasks to be achieved, the application of tribology, and especially of green tribology can provide a breathing space which would enable scientists and technologists to find solutions to these, mankind’s crucial problems and allow time for them to be implemented by governments, organizations and indeed everyone operating in this important field. Consequently, this important—albeit limited—breathing space may be extremely valuable to all working for the survival of life as we know it. However, the ultimate key is science and its application. Tribology—especially green tribology can and—I am confident—will play its part to assist and give time for science to achieve the required solutions and for policy makers to implement them’.

5. Conclusions

Green tribology is a novel area of science and technology. It is related to other areas of tribology as well as other ‘green’ disciplines, namely, green engineering and green chemistry. We have formulated the 12 principles of green tribology and defined three areas of tribological studies most relevant to green tribology. The integration of these areas remains the primary challenge of green tribology and defines future directions of research.

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