Biotribological model systems for emerging nanometer scale technologies

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***Abstract*- Technological devices such as pressure sensors, gyroscopes and accelerometers get smaller and smaller. This increases the necessity for the fundamental understanding of tribological phenomena at the micro- and nanometer scale. Biological systems excel also at this scale.**

The thesaurus that nature has developed during the last millions of years of evolution comprises self-cleaning surfaces, systems with friction coefficients smaller than any occurring in man-made systems and organisms that produce macromolecules with ice binding properties. Such systems with well adapted biotribological properties shall serve as inspiration for innovation in micro- and nanotechnology.

I. INTRODUCTION

Tribology is the field of research dealing with friction, wear and lubrication of surfaces in relative motion. Tribology aims at optimization of such systems in functional, economical and environmentally friendly ways.

Proper application of tribological knowledge leads to less wear and optimized friction conditions, and thereby increased safety of machines and equipment, lower production costs and less energy consumption and emissions.

Tribology is relevant in fields as diverse as mechanical engineering, production technology, automotive industries, (aero)space technology, building technology, energy supply, electronics engineering, medical technology and precision engineering.

Because the parts used in such technologies continuously become smaller, microtribology and nanotribology gain more and more importance [1,2].

Macrotribological relations cannot simply be scaled down to the nanometer scale. The "smooth surface" or the Hertzian contact used in the Hertz model to calculate the common contact area of a ball and a flat sample under compression are not valid concepts any more in the nanometer regime. The length scale and the large surface to volume ratio of MEMS and NEMS result in large retarding forces concerning friction and adhesion that seriously undermine reliability and performance [3].

The new fields of micro- and nanotribology receive valuable input from biological systems. After all, biological systems had millions of years to adapt. Tribological issues have been addressed in various, sometimes unconventional and counterintuitive ways. Innovative approaches to new lubricants, designs and materials can be expected from natural systems.

In biomimetic engineering, new technology is based on principles used by biological systems. A famous example is Velcro. It was invented and patented by George de Mestral after he realized how strong the little organic hooked spines of a plant stuck to the fur of his dog. Today, selling Velcro is a multi-million dollar business [4].

In their book on biological micro- and nanotribology, Scherge and Gorb [5] present a wide compendium of "biological tribosystems", ranging from systems with reduced friction, such as joints, to systems with increased friction, such as interlocking devices in bird feathers via elastic hooks, or the attachment pads of the gecko.

They also present systems with increased adhesion, such as the sticking pads of tree frogs, and systems with anti-sticking mechanisms, as can be found in self-cleaning surfaces of plants and animals such as the dung beetle. The lotus effect [6] gained huge attention, and is currently exploited in a multitude of industrial applications, ranging from self-cleaning paint for cars or houses to anti-sticking coatings for the inside of containers.

Bionanotechnology exploits the fact that evolution has led to very powerful and efficient nanomachines. We can now, for example, separate components of biological cells and, to a certain extent, run them outside the organism. Already in 2000 Montemagno and coworkers succeeded in combining biology and nanotechnology: they constructed one of the first bionanomechanical devices: an array of biological molecular motors on nickel posts (height 200 nm, diameter 80 nm). Propellers of 750-1400 nm length and 150 nm diameter attached to the rotor of each motor start rotating after the addition of adenosine triphosphate, a high energy phosphate molecule used to store and release energy for work within biological systems [7].

Biological molecular nanomachines such as the molecular motor used by Montemagno and coworkers are defined in their structure down to each single atom. Wear in such devices

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would change their conformation and in many cases render them infunctional. Therefore, these natural nanomachines have evolved also under the constraints concerning their tribological performance given by the environment in which they function. Especially for man-made nanomachinery utilized in physiological conditions such as nanorobots in the blood stream (for targeted drug delivery or for repair of pathological conditions), elucidating the basic building principles in biological nanomachines will help to optimize the performance of man-made nanodevices and allow for development of more reliable, efficient and environment-respecting materials [8].

One large obstacle in current man-made micro- and nanomachines is their tendency to aggregate. Biological nanomachines have such highly engineered functional surfaces that they usually only aggregate in pathological conditions. An example for this is the aggregation of misfolded proteins with exposed hydrophobic groups. And even for such cases, structures have evolved that repair this machinery: molecular chaperones are proteins whose function is to assist other proteins in achieving proper folding [9].

The best way to investigate building principles concerning optimization to different parameters might be in conditions where the relevant parameter is extreme. Many organisms thrive at extreme conditions, such as temperature, pH, and the like [10, 11]. In a famous case such an extremophile inspired approach yielded a Nobel Prize, lots of money and the basis for a standard technology of quickly replicating DNA: the polymerase chain reaction, PCR.

The high efficiency of biological systems shows us the actually reachable limits. Without living proofs such as plants, animals or people it might be hard to imagine that single photon detectors exist, in which one single photon elicits hundreds of transduction molecules within one millisecond. In fact, the human eye is such a sensitive detector: it can detect a single photon falling on the retina. This photon is then absorbed by a molecule called rhodopsin. The resulting nerve impulse has an energy at least a million times larger than the energy contained in the original photon [12]. Such powerful signal amplification cascades are present throughout the sensory system.

Another example of signal detection sensitivity that is yet to be reached with man-made technology is the amazingly low hearing threshold in humans: signals below the thermal noise can be detected, and in fact the noise even helps to detect these small signals instead of blurring them [13, 14]. This happens via the principle called stochastic resonance. For an overview on stochastic resonance in biology see [15].

The following sections present two systems with well adapted biotribological properties: articular cartilage, a bioactive surface lining the bones in joints such as the hip, the shoulder or the knee, which has a friction coefficient of only 0.001 [16]; and diatoms, micrometer-sized organisms producing nanostructured glass and self-healing underwater adhesives. The diatoms have rigid parts in relative motion, and might serve as model systems for innovations in micro- and nanotechnology [17, 18].

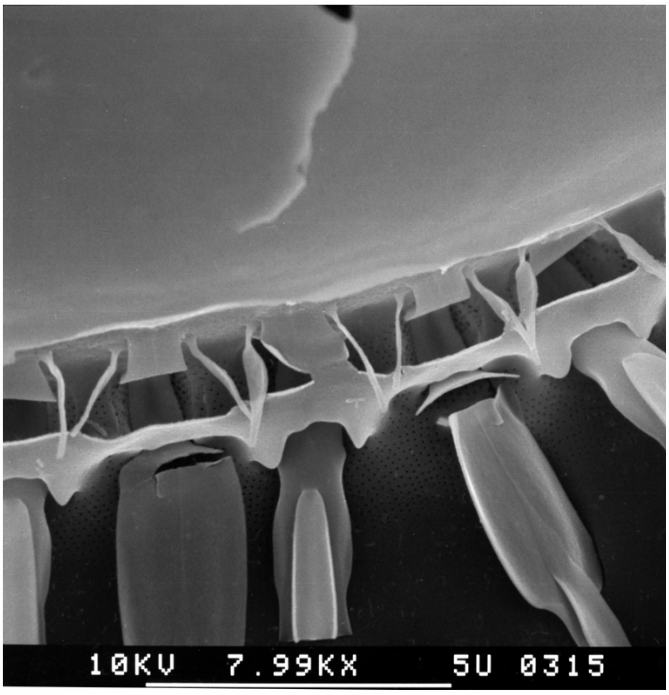

Fig. 1. Scanning electron micrograph of a surface detail in the diatom species *Corethron*. When new cells are mature after cell division, they expand and allow their spines to swing out to adopt their final position. In doing this they move past a click-stop that prevents them moving too far back from their required position. Scale bar 5 µm. © R.M. Crawford, AWI Bremerhaven.

II. Low Friction Coefficient - Natural Synovial Joints

In nature exceptional designs for interfacing soft and hard materials with capabilities well beyond present day technologies have developed. A major challenge is to extract design lessons from nature especially for the interface of soft (organic) and hard material that are mechanically, chemically and electrically compatible.

Articular cartilage (AC) is the cartilage that lines bones in joints. AC is a functionally gradient material (FGM). In FGMs a continuous spatial change in composition or microstructure gives rise to position-dependent physical and mechanical properties that can extend over microscopic or macroscopic distances [19].

AC is the bearing surface with low friction and wear in freely moving synovial joints that permits smooth motion between adjoining bony segments [20]. Because of its compliance, AC helps to distribute the loads between opposing bones in a synovial joint. Hip, knee, elbow, fingers, shoulder and ankle are examples of synovial joints [21]. Synovial joints are complex, sophisticated systems not yet fully understood. The loads are surprisingly high and the relative motion is complex.

The entire joint is enclosed in a fibrous tissue capsule, the inner surface of which is lined with the synovial membrane that secretes a fluid known as synovial fluid. Synovial fluid is essentially a dialysate of blood plasma with added hyaluronic acid. In a common joint less than 1ml of synovial fluid is present.

Synovial fluid is a thick, stringy fluid. With its egg-like consistency (the term synovial stems from Latin for "egg" and was introduced by Paracelsus) synovial fluid reduces friction between the articular cartilage in joints to lubricate and cushion them during movement.

Articular cartilage is a nanocomposite material. About 70 to 85% of its weight is water. About 30% of the dry weight is composed of high molecular weight proteoglycans and 60 to 70% of the dry weight is made up of a network of collagen, a fibrous protein with huge tensile strength.

Normal synovial joints operate with an amazingly low coefficient of friction. Some groups report friction coefficients as low as 0.001 [22-24], generally slightly higher values (between 0.002 to 0.006) appear in the literature [e.g. 25, 26]. Values of up to 0.02 are reported for the friction coefficient in synovial joints. One reason for the huge variation in the hip joint friction coefficient might be its distinct temperature dependence (S. Chizhik, personal communication). Such low friction coefficients are still hard to reach with man-made systems. For comparison, Teflon sliding on Teflon (or Teflon sliding on steel) has a coefficient of friction of about 0.04, this is an order of magnitude higher than that for synovial joints.

In biological systems especially, however, friction and wear are not simply related phenomena [27, 28]; low friction systems do not necessarily result in low levels of wear. Since worn material can be replaced (re-grown) by many biological systems, low friction is in many cases more preferable than low wear.

Identifying the mechanisms responsible for the low friction in synovial joints has been an area of ongoing research for decades. Furey lists more than 30 theories that have been proposed to explain the mechanisms of joint lubrication [29].

In summary, articular cartilage provides an efficient load-bearing surface for synovial joints that is capable of functioning for the lifetime of an individual. The mechanical behaviour of this tissue depends on the interaction of its fluid and solid components.

In 1743, Sir William Hunter read to a meeting of the Royal Society "Of the structure and diseases of articulating cartilages". This classic paper starts with the following words:

"The Fabric of the Joints in the Human Body is a subject so much the more entertaining, as it must strike every one that considers it attentively with an Idea of fine Mechanical Composition. Wherever the Motion of one Bone upon another is requisite, there we find an excellent Apparatus for rendering that Motion safe and free: We see, for Instance, the Extremity of one Bone molded into an orbicular Cavity, to receive the Head of another, in order to afford it an extensive Play. Both are covered with a smooth elastic Crust, to prevent mutual Abrasion; connected with strong Ligaments, to prevent Dislocation; and inclosed in a Bag that contains a proper Fluid Deposited there, for lubricating the Two contiguous Surfaces. So much in general."

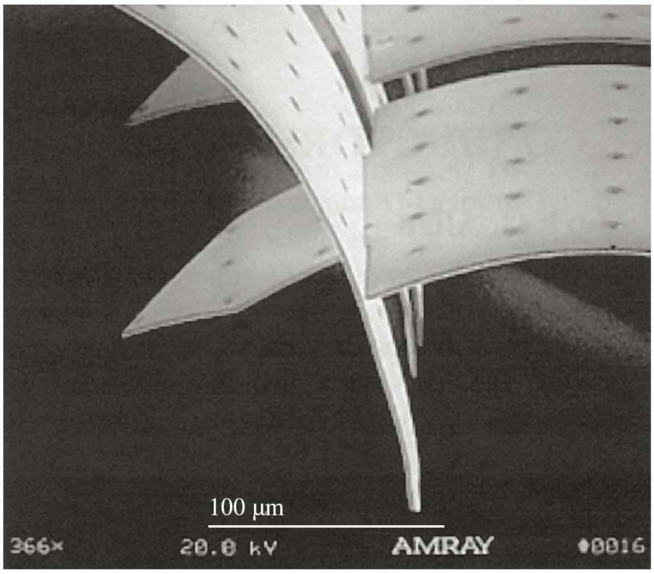

Fig. 2. Detail of a self-assembled out of plane coil MEMS that has been fabricated using micromachining technology. The inductor winding traces interlock into each other to form coil windings. Scale bar 100 µm. Reprinted with the permission of the author and the Transducer Research Foundation from: C.L. Chua, D.K. Fork, K.V. Schuylenbergh, and J.P. Lu, "Self-assembled out-of-plane high Q inductors," *2002 Hilton Head Solid-State Sens. Actuator Workshop*, Tech. Digest pp. 372-373 [41].

Since then, a great deal of research has been carried out on this subject. And yet, the mechanisms involved are still unknown. Further investigation of the complex field of joint lubrication will improve our understanding of this amazing system, help to develop effective pharmaceuticals for people suffering from arthritis and provide innovative ideas for new materials and technologies.

III. Tribology in Glass on the Micrometer Scale - Diatoms

Diatoms are single celled organisms that live either in the sea or in freshwater. They can be attached to a substratum (benthic diatoms) or live freely floating in the ocean. For an overview on diatoms, see [30]. Diatoms produce nanostructured silica. Many of the benthic diatoms produce adhesives. The silica production at ambient temperatures is interesting for materials scientists and structural biologists and is an active area of research (see e.g. [31]).

The adhesive production of diatoms is on the one hand a tedious problem for marine devices (biofouling). On the other hand, these adhesives are interesting for materials scientists and tribologists. Most man-made underwater adhesives are not stable in the seawater, and getting ideas from these natural, strong, and in many cases even self-healing adhesives might bring some new ideas to engineers working on the development of novel adhesives [32, 33, 34, 35].

There are even diatoms in the far north and south of the earth: more than 100 diatom species have been described from the polar regions. Some of them are planctonic forms, i.e. freely floating in the water, and some are benthic forms, i.e. they are attached to some kind of substratum. Examples for antarctic benthic diatoms are *Gyrosigma subsalinum* and *Odontella litigiosa*. It has been shown that not only carrots [36] but also some diatom species produce substances that strongly inhibit the recrystallisation of ice [37]. These substances have not yet been identified, but experiments with purified solutions produced from samples collected in polar regions show that these substances bind to specific crystal orientations of the ice, and are also incorporated into the ice lattice. Unlike fish antifreeze proteins [38], they do not significantly reduce the freezing point. These substances are very stable, even heating them to 100 degrees Celsius for five minutes does not affect their ability to inhibit recrystallisation. The temperature stability of these substances might be important in technological applications, e.g. in coating wind shields of airplanes with thin layers of such a recrystallisation inhibitor.

The crystal orientation specific etching of these substances reminds of the proteins guiding and inhibiting snail shell growth, via selectively promoting or preventing calcium carbonate growth in specific crystal orientations [39].

Several diatom species have evolved elaborate linking structures [18]. Hinges and interlocking devices serve several functions: they keep the cells together (anti-dispersal strategy), they keep the cells apart, so that enough light for photosynthesis can enter the cell. A diatom species named *Corethron* has evolved a click-stop mechanism for the silica spines that prevents them moving too far back from their "required" position (Fig. 1). The whole structure is beautifully engineered in miniature [40] and might provide valuable ideas for novel self-assembled MEMS such as the out-of-plane coil inductors (see Fig. 2 for a detail of the interlocking trace, reprinted with permission of the author and the Transducer Research Foundation from [41]).

IV. DISCUSSION

Here we present several examples of well adapted biological systems that demonstrate the possibilities biology can offer technology.

Systematic technology transfer from biology to micro- and nanoengineering might be very beneficial for emerging nanometer scale technologies [42]. For future fruitful collaboration between biologists and engineers, linkers are needed, i.e. researchers who speak the languages of both disciplines and who can transfer knowledge from one field to the other.

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