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A Detailed Review of Functional Surface Design in Bionic Tribology

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Abstract

Bionic tribology, a new couping of biology and tribology, provides a new angle to solve an urgent problem concerning friction-wear-lubrication. This review systematically presents the basic rules of biomimetic surface design for natural biological systems which possess excellent tribological properties as inspiration. Detailed design strategies such as micro/nano- structure fabrication, surface modification and material selection are introduced in terms of the latest progress in the manufacturing technologies. Typical applications in aerospace, automotive, biomedical as well as marine engineering are discussed with the focus on the improvement of physical attributes and technological developments. Current bottlenecks in manufacturing scalability, durability under harsh conditions and theoretical modeling are discussed to compare and contrast the proposals together with outlooks for future research and perspectives like machine learning-assisted design and multifunctional adaptive surfaces. It is hoped that this comprehensive review on design, fabrication and applications of bionic tribological surfaces will facilitate the sustainable engineering.

Keywords: Bionic Tribology, Functional Surfaces, Micro/Nano-Structures, Biological Inspiration, Surface Engineering, Manufacturing Technologies

Introduction

The study of tribology, relating to the design and function of interacting surfaces and motion, is critical to many aspects in modern engineering such as energy efficiency, material durability and system reliability. Worldwide, almost 23% of the primary energy is lost due to friction and wear at an annual cost of over $1.2 trillion [1]. In vehicle applications, up to 30% of the fuel energy in automobiles is lost to frictional power losses in engines and powertrains, and aeroplanes incur considerable drag penalties owing to surface-turbulent interactions [2]. In the field of medical equipment, inflammation in response to wear debris from implants can reduce the life of such devices [3]. Classical tribo-systems, namely fluidic coatings and hard material solutions, are restricted in severe conditions and deep dynamics. For example, liquid lubricants can evaporate in aerospace applications, while solid coatings such as PTFE have low wear resistance under heavy loading [4]. These difficulties call for new approaches to fabricate the materials in which the low friction and wear-resistant properties are sustainable.

The Paradigm Shift: Bionic Tribology: Bionic tribology can provide a new direction by modelling the evolutionary solutions in nature. Natural systems such as those in living organisms, which are nature's solution to tribology, have sophisticated surface structures and actions that have been honed over millions of years to deliver outstanding tribological performance. Notable examples include:

- **Shark skin**: V-shaped riblets (50–200 μm in height) that reduce drag by aligning turbulent eddies in the boundary layer.
- **Lotus leaves**: Hierarchical micro-papillae (5–10 μm) covered with nanowax crystals facilitating superhydrophobicity and self-cleaning.
- **Gecko feet**: Nanoscale setal arrays (0.2–1 μm) that generate strong van der Waals adhesion through high-aspect-ratio structures.

Inspired by these biological examples, engineers can create such functional surfaces with improved tribological properties. Bionic design is compared with conventional product design in three ways: Natural surfaces often exhibit structures spanning micro to nano scales, enabling synergistic functional integration. Biological systems can respond to environmental changes. Biomaterials such as nacre exhibit extraordinary toughness due to their tuned composite architectures[5].

Scope and Structure of This Review: Design principle, fabrication methods and applications of bionic tribological surfaces are mainly discussed in this review. It is structured as follows:

- **Section 1** presents fundamental knowledge of tribology and bionics, such as friction mechanisms and bio-inspiration.
- **Section 2** discusses strategies in the design of surfaces, including micro/nano-structure engineering, surface chemistry and material selection.
- **Section 3** Fabrication technologies ranging from top-down lithography to bottomup selfassembly are reviewed.
- **Section 4** presents applications across industries, supported by case studies and performance data.
- **Section 5** discusses the present challenges, and the perspective aspects such as multifunctional surfaces, and computational design.

Fundamental Concepts of Tribology and Bionics

Friction results from the contact between two surfaces under relative movement, and is controlled by both mechanical interlocking of asperities but also adhesive forces at nano level. The model consists of a friction force described by the classic Coulomb's law $F=\mu N$, the friction coefficient and N the normal load. Modern tribology does however consider multiple friction regimes:

- **Adhesive friction**: Controlled by the intermolecular forces at the junction between asperities. For instance, in case of a metal-on-metal interface the adhesive friction is significantly large because of strong metallic bonding [6].
- **Abrasive friction**: his occurs when hard particles plow into a softer surface, such as effects observed in sandpaper wear and wear of ceramic bearings [7].

- **Fluid friction**: he first one is lubricating or fluid friction, which happens in lubricated system where the resistance coefficient depends on viscosity, film thickness and surface roughness (similar to the Stribeck curve) [8].

Friction is highly dependent on surface roughness (characterized using parameters such as Ra and Rq). For example, a shark-skin riblet surface changes the near-wall flow structure and decreases μ by 8–12% compared with a smooth surface [9].

Wear Mechanisms: Due to foreign material (running contacts), which is pressed on (e.g., adhesion of tyre rubber to a road surface) . When surfaces bond and tear apart, resulting in material transfer (in metal gears, this is known as galling). Due to cyclic loading, micro-cracks form and then spread or break (such as with bearing raceway spalling). Resulted from particle impact (i.e., in aircraft engines or marine propellers). Wear is counteracted in biological systems. As an example, the teeth of garden snails and chitons possess hierarchical chitin-mineral composites that are 500 times more wear resistant than pure chitin[10].

Lubrication Strategies: Friction and wear are diminished by the use of a lubricant to provide a film between the moving surfaces:

- **Hydrodynamic lubrication**: Fluid pressure carries the load (e.g., engine oil in bearings).
- **Elastohydrodynamic lubrication (EHL)**: The surfaces deform elastically to create a film of the lubricant (e.g., in gear contacts).
- **Boundary lubrication**: Lubricant molecules adhere to surfaces and reduce adhesive forces (e.g., fatty acids in metalworking fluids).
- **Self-lubrication**: Biological systems such as articular cartilage produce synovial fluid that can alter its viscosity under load.

There have been three basic approaches to learn lessons from biological tribology and convert them into engineering science in bionic tribology:

Structure-Property Relationships: Some revelation to improve the tribological properties are seen when scanning natural surfaces revealing a hierarchical scales of structure:

- **Shark skin riblets**: These V-grooves (spacing S ≈ 200 μm, height h ≈ 100 μm) – see Figure 1- align the turbulent eddies so that the drag is reduced because of a modification of the Reynolds stress distribution [11]. Wind tunnel tests have demonstrated that riblet films on aerofoils reduce drag by 6–8% translating to 3–5% fuel saving for commercial aircraft [12].

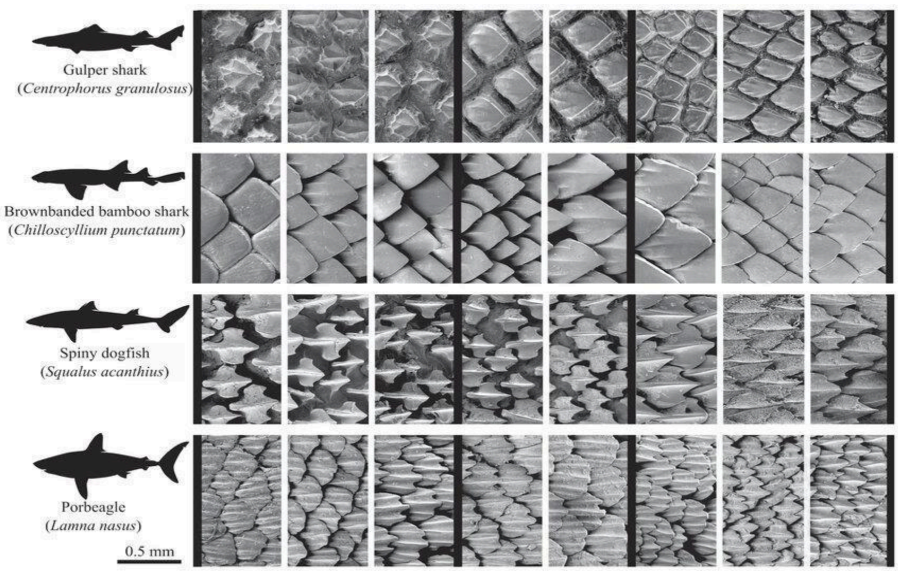

Figure 1: SEM image of shark skin riblets and flow modification schematic

Source: [Fletcher T M 2015.]

- **Lotus leaf microstructure**: Micro-papillae (5–10 μm) with nanowax coatings (200–500 nm) realize a Cassie-Baxter state and water droplets reside on the top of structures, which results in a contact angle >150° and low sliding angle <5° [13]. The superhydrophobic nature reduces the adhesion of liquid and contamination on it.

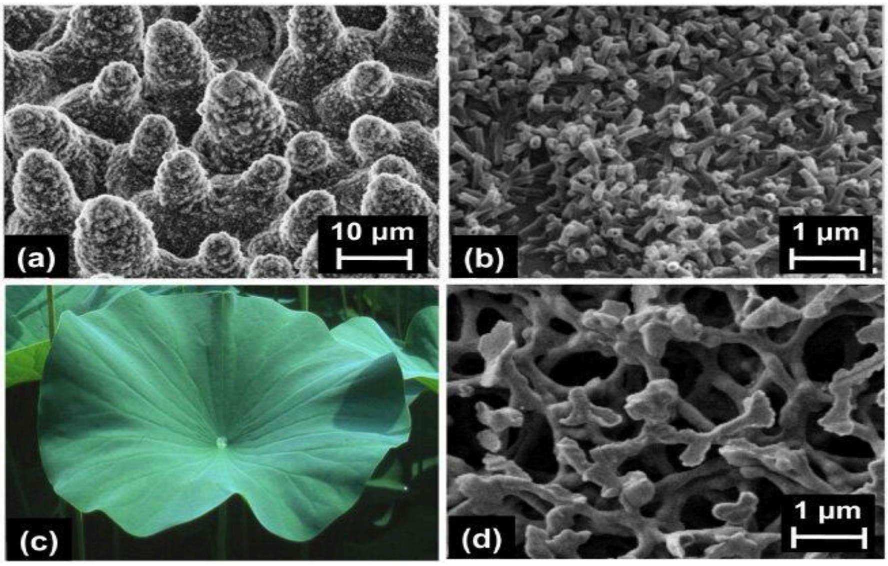

Figure 2: (a) Scanning electron microscopy of a lotus leaf microstructure and (b) a Lotus leaf nanostructure; (c) Lotus leaf and (d) Whatman BA85 Protran nitrocellulose nanostructure. [Source: Nanotechnology (2014)]

Functional Adaptation: Dynamic responses of biological systems Biological systems often have dynamic responses to environmental changes. Chondrocytes in cartilage secrete hyaluronic acid under load, elevating the viscosity of the lubricant and thus reducing friction. Geckos can transition from high-adhesion (needed for climbing) to low-adhesion (needed to release themselves by sliding setae at the end of each step). This concept serves as motivation for robotic grippers with reversible adhesive tapes.

Material Selection and Composite Design: Ragonite platelets with an organic matrix in a "brick-and-mortar" arrangement contribute to toughness by crack deflection and pull-out. Synthetic nacre-like composites present 300% improved fracture resistance than monolithic ceramics [14,15]. Hierarchical Protein Structure (Nanofibrils, Microfibrils, Fasern) High tensile strength (400–2000 MPa) and elasticity as a template for lightweight wear-proof coatings.

Table 1. Biological Models and Their Tribological Applications

Biological Model	Structural Feature	Tribological Function	Application Example	Performance Enhancement
Shark Skin	Riblet Microstructure (50–200 μm)	Drag Reduction	Aircraft Wings [29]	6% fuel savings
Lotus Leaf	Hierarchical Roughness (micro-papillae + nanowax)	Superhydrophobicity, Self-Cleaning	Anti-Fouling Coatings [30]	Contact angle >150°, sliding angle <5°
Gecko Feet	Nanoscale Setal Arrays (0.2–1 μm)	Adhesion Control	Reusable Adhesives [31]	Adhesive strength ~10 N/cm^2
Cicada Wing	Nano-Pillar Structure (100–500 nm)	Anti-Biofouling	Medical Devices [32]	90% reduction in bacterial adhesion
Beetle Elytra	Textured Surface with Pores	Self-Lubrication	Self-Lubricating Bearings	Friction coefficient <0.05

Design Principles of Bionic Tribological Surfaces

Drag-Reducing Structures: Shark Skin and Beyond: Shark scale-mimicking riblet is one of the well-studied bionic tribological microtexture designs. The optimal riblet geometry (height h, spacing S, and aspect ratio h/S) depends on the Reynolds number (Re) of the flow:

- For aircraft applications (Re ~ 107), optimal $h \approx 100\mu m$, $S \approx 200\mu m$, reducing turbulent friction by disrupting near-wall vortices [33].
- In microfluidic devices (Re ~ 10–100), smaller riblets (h ~ 1–10 µm) minimize viscous drag.

And other living models also inspire drag-reducing structures beyond shark skin:

- **Dolphin skin**: A soft, compliant, hydrodynamic... flexible composite material whose geometry and underlying molecular composition suppresses turbulent drag through action of viscoelastic damping. Artificial imitations based on silicone elastomers with embedded microchannels demonstrate 15% drag reduction in water .
- **Manta ray fins**: Trailing-edge protrusions that create spiral vortices to keep lift at lower speeds, cutting down on drag. Wind tunnel tests : In AEROFOILS - 20% increase in lift/drag ratio.

Superhydrophobic and Self-Cleaning Surfaces: The principle of lotus effect guided design of antifouling from the structure induced hierarchical roughness, as well as low surface energy chemistry:

- **Micro-nano hierarchical structures**: By combining micropillars (5–10 µm) with nanoprotrusions (200–500 nm), the composite interface can effectively entrap air, limiting liquid contact area. For instance, contact angles >160° and sliding angles <2° are obtained when the PDMS surfaces possess such structures.
- **Bio-inspired self-cleaning coatings**: To emulate the wax crystal layers on plant leaves, fluorinated silanes or nanoceramic composites are coated on building surfaces and they have up to 80% less dust.

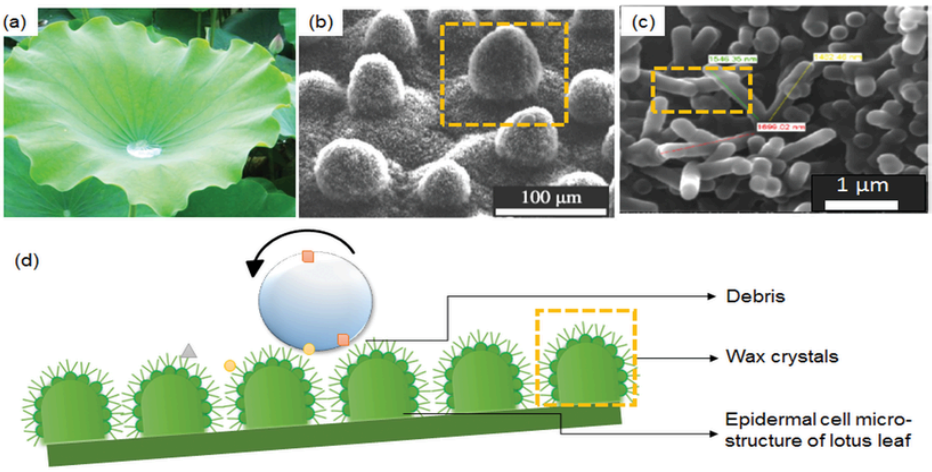

Figure 3: a) Self-cleaning effect of lotus leaf (lotus effect). b) SEM micrograph shows microstructures of lotus leaf surface c) Reproduced with permission. d) Schematic representation of the self-cleaning effect of lotus leaf (lotus effect). [Source: Taylor & Francis Ltd(2009), Elsevier B.V. d (2009)]

Adhesion and Anti-Adhesion Systems: Biological adhesion systems span a wide range of scales, from gecko feet to insect claws:

- **Gecko-inspired dry adhesives**: Polyurethane nano-fibrillar arrays (diameter ~500 nm, height ~10 µm) generate strong van der Waals forces. These adhesives can support up to 10 N/cm² and are reusable over 1000 cycles [16].
- **Anti-adhesive surfaces for biomedical applications**: Nano-pillars formed on cicada wings (100–500 nm) break the integrity of bacterial cell membranes by killing 90% attached E. coli for a period of time, up to 2 hours [17]. Such surfaces are being worked on for catheters and implants to stop biofilm developing.

Hydrophobic/Hydrophilic Coatings: The natural surfaces are characterized by a combination of a structural roughness and chemical function:

- **Plant leaf waxes**: Aliphatic hydrocarbons and fatty acids (C20–C30) reduce surface energy to <20 mN/m with regard to the increase in water repellency. Synthetic counterparts employ fluoropolymers (e.g., PTFE, surface energy ~18 mN/m) or silanes (e.g., octadecyltrichlorosilane, ~24 mN/m) [18].
- **Hydrophilic biomedical surfaces**: When coated with polyethylene glycol (PEG) to mimic the glycoprotein layer of a cell membrane, in vitro protein adsorption decreases by 95% and cellular attack diminishes due to increased biocompatible affinity [19].

Chemical defence as a tool to either avoid or resist fouling is used by biological systems: Peptides such as magainin that are found on frog skin can kill bacteria by disrupting their membrane. The synthetic AMP-mimicking polymers lined onto surgical devices also decrease attachment of bacteria by 99% . TiO_2 -motivated photocatalytic leaves Plants develop titanium dioxide (TiO_2)-like nanoparticles in their tissues which, when UV is available, led to the formation of reactive oxygen species resulting in the degradation of organic pollutants. These are the type of coatings in self cleaning windows which means 70% less detergent! . Inspired by the mucus layer in stomach, hydrogel surfaces that release lubricant (e.g., hyaluronic acid) at low pH (under acidic environment) have been developed for artificial joints. Friction coefficients reduce from 0.3 to 0.05 with acidic loads. Based on the adhesive organs of some beetles, where polymers such as poly(N-isopropylacrylamide) result in another sticky-to-non-sticky change from above 32°C and thus also possess programmable adhesion.

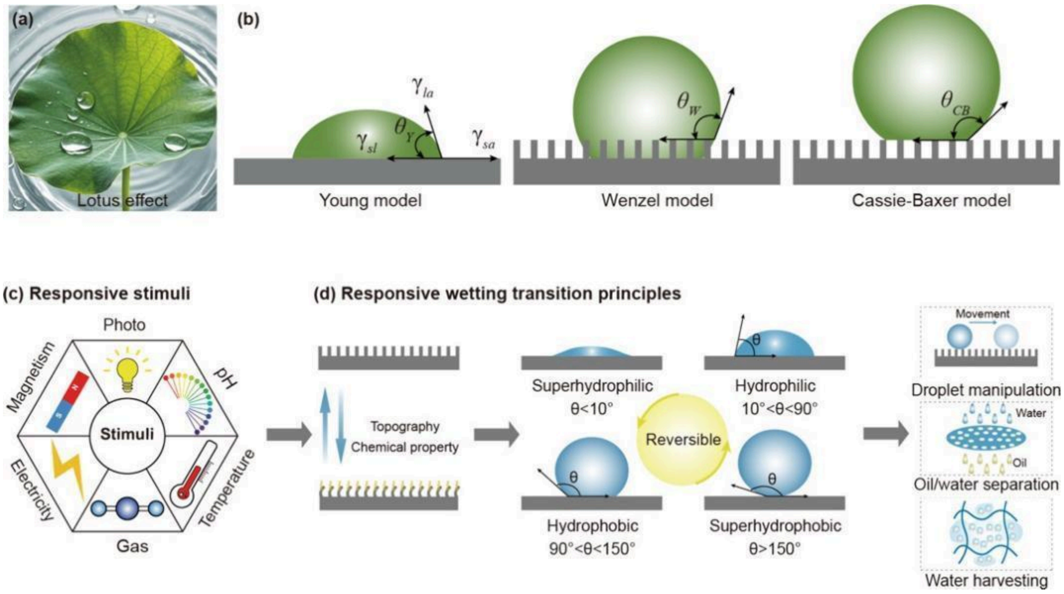

Figure 4: Adaptive Surfaces with Stimuli-Responsive Wettability [Source: ACS Nano 2025]

Material Selection and Composite Design: Biomimetic Engineering

Nacre-Like Composites: The "brick-and-mortar" architecture of nacre provides a model for hard-wearing yet tough materials:

- **Structure replication**: Alternating layers of ceramic (e.g., Al_2O_3, 50–100 µm thick) and polymer (e.g., epoxy, 5–10 µm thick) form composites with fracture toughness (15–20 $MPa \cdot m^{1/2}$) 3–5 times higher than monolithic ceramics.
- **Application in cutting tools**: 40% higher lifetime of engineering ceramic composite carbide-cobalt cutting tool when turning, due to improved transcrack deflections.

Microcapsule, embedded in polyurethane coatings and filled with healing agents such as dicyclopentadiene (50 –100 µm), are capable of mending superficial scratches on their own. Upon crack initiation, capsules burst open and contents are released and polymerize to close the damage [20]. Dependent on the imitation of blood vessels, channels (100–500 µm) are embedded into bearings and deliver lubricant on request. 80% less wear is induced by this system that static lubrication [21]. Electrospun poly(ethylene terephthalate) (PET) fibers with oriented nano-crystals reach tensile strengths of 1.2GPa, very close to natural silk (1.5GPa). They are utilized for wear-resistant, light coatings into which gears are sunk. Mimicking the structure of mineral-organic phases of bone, nano-HA (nHA) reinforced with collagen fibers produce materials that have an elastic modulus (10 – 20 GPa) similar to natural bone and decrease in stress shielding.[22]

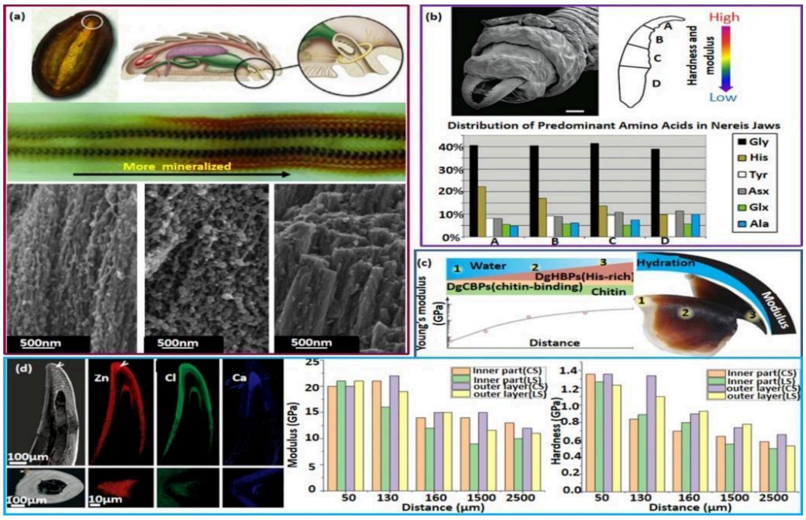

Figure 5: The regulation of composition to achieve different properties. a) The gradient mineralization of radular teeth of chiton; b) The distribution of different type of amino acid in the nereis jaws; c) The diverse site-specific modulus induced by distinction of hydration; d) The distribution of different ions in the fang of spiders [Source: Bioinspired Strategies for Excellent Mechanical Properties of Composites 2022]

Fabrication Techniques for Bionic Tribological Surfaces

Top-Down Approaches: Precision Patterning

Lithography Techniques:

- **Photolithography**: Uses light to transfer patterns from a mask to a photoresist layer, suitable for micro-scale features (1–100 μm). For example, shark skin riblets with 200 μm spacing are fabricated on polycarbonate films using UV photolithography, followed by hot embossing [23].
- **Electron Beam Lithography (EBL)**: Nanoscale (< 10 nm) resolution is obtained by scanning an electron beam across a resist. Here, EBL is exploited to pattern gecko-mimetic nano-setal arrays (of diameter ~200 nm) onto silicon wafers. [24] However, the EBL is a slow technique (EDM rate 1 mm² / hour), hampering the fabrication of large-area F produces.
- **Nanoimprint Lithography (NIL)**: Presses a patterned stamp into a soft material (e.g., PDMS), replicating features down to 10 nm. NIL is cost-effective for mass-producing lotus leaf-like superhydrophobic surfaces, with throughputs exceeding 10 m²/hour [25].

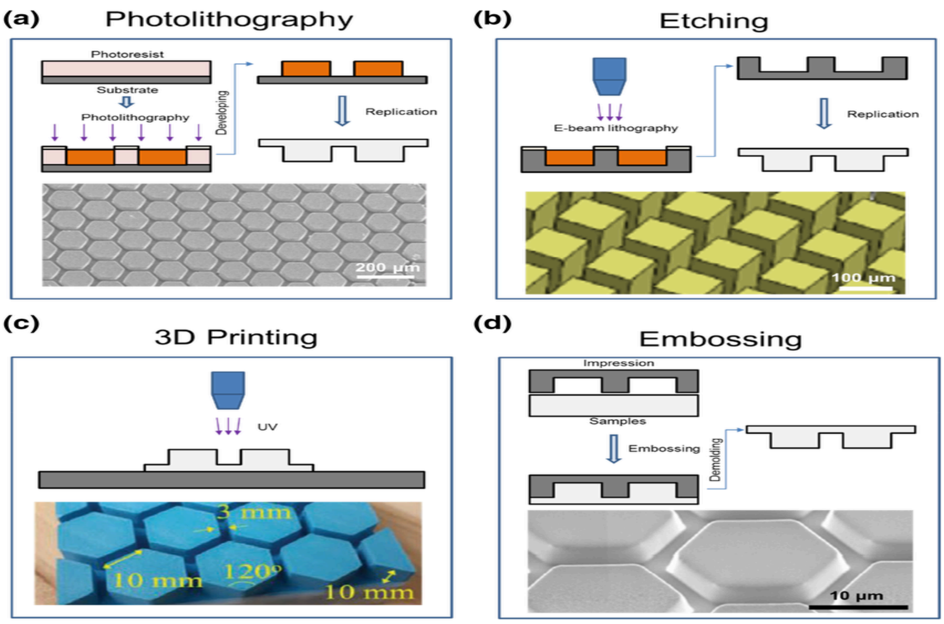

Figure 6: Top-down approaches include (a) photolithography and (b) etching. Bottom-up approaches include (c) 3D printing and (d) embossing. [Source: Adv. Sci., Ref. [53], (2020); IEEE Robot. Autom, Ref. [51], (2019); Adv. Mater. Interfaces., Ref. [38], (2020); Biointerphases. Lett. (2019)]

Etching and Milling: Uses plasma to etch materials anisotropically, creating vertical nano-pillars. For example, RIE of silicon produces arrays with aspect ratios >10:1, mimicking cicada wing structures. Ultra-short laser pulses (10^{-15} seconds) ablate materials with minimal heat damage, enabling 3D micro/nano structuring. Laser-textured titanium implants show 50% higher cell adhesion due to hierarchical roughness. Precisely machines micro-riblets on metal surfaces (e.g., aluminium alloys) with roughness $Ra < 50\ nm$, suitable for aerospace applications.

Bottom-Up Approaches: Self-Assembly and Growth

Self-Assembly Techniques: Amphiphilic block copolymers (e.g., polystyrene-block-poly(methyl methacrylate)) form periodic nanostructures in thin films on a scale of 10–100 nm. With this technique, anti-fouling surfaces with nano-hexagonal pits that suppressed protein adsorption by ~70% were fabricated. Sequentially deposits polyelectrolytes, e.g., poly(allylamine hydrochloride) and poly(sodium 4-styrenesulfonate), for the fabrication of multilayered films. Materials and methods: LbL has been developed on catheters that include antimicrobial peptides, which can kill 99% of adhered bacteria. Monodisperse (100 nm–1 μm) microspheres self assembles ordered arrays by sedimentation. These are used as templates for inverse structures. Silica spheres, for instance, self-assemble in to opal structures that are etched to form superhydrophobic nanopores.

3D Printing and Additive Manufacturing:

- **Stereolithography (SLA)**: It cures liquid resins with UV light and achieves <100 μm resolution to build complex geometries. Lotus leaf-like textured soft prototypes of SLA-printed bionic bearings exhibit 30% less wear compared to the smooth bearing [26].
- **Fused Deposition Modeling (FDM)**: Contains thermoplastic filaments and builds structures layer by layer. FDM Printed shark skin riblets gears reduce friction up to 15% [27].
- **Two-Photon Polymerization (TPP)**: Inducing a photopolymerization inside a material volume using femtosecond lasers to achieve nanoscale feature sizes (~100 nm). Likewise, TPP is used to fabricate gecko-adhesive pads with 500 nm setae [28].

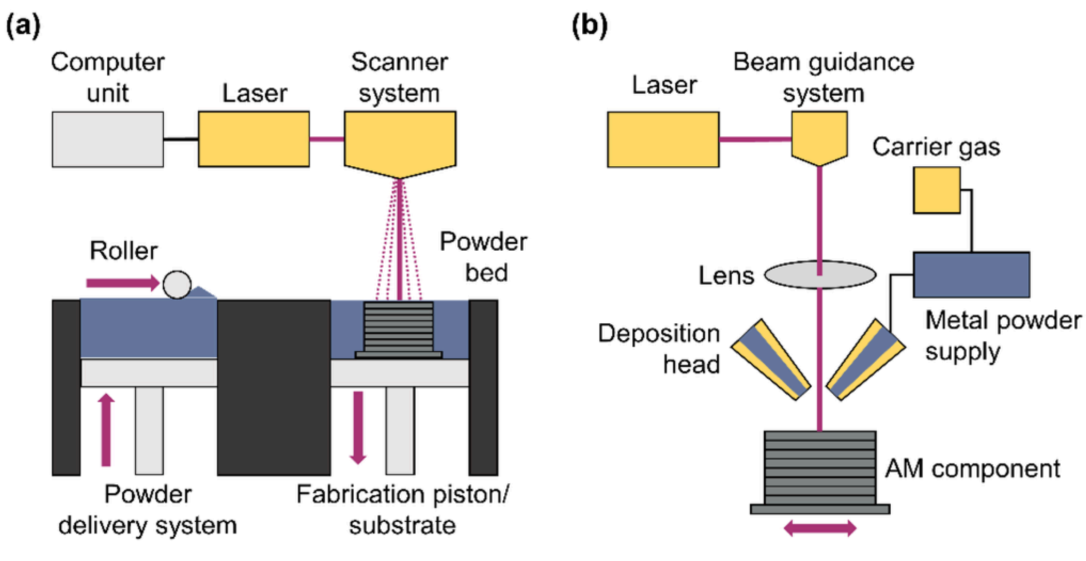

Figure 7: Schematic diagram of (a) direct metal laser sintering (DMLS) or selective laser melting (SLM) and (b) direct energy deposition (DED) processes. [Source: JMMP CC 4.0]

Hybrid Methods: Integrating Scalability and Precision: Electrospinning produces polymer nanofibers (100 nm–1 µm diameter), which are then coated with nanoparticles (e.g., TiO_2) to create superhydrophobic surfaces. These mats, inspired by spider silk, exhibit self-cleaning and UV resistance . Electrospun microfibers (1–10 µm) with nano-beads on their surface mimic the dual-scale roughness of lotus leaves, achieving contact angles >160° .

Plasma etches create micro-roughness, followed by CVD deposition of low-surface-energy films (e.g., fluorocarbons). This hybrid method produces superhydrophobic surfaces on metals with durability exceeding 1000 abrasion cycles . Plasma deposits thin, cross-linked polymer films (10–100 nm) with tailored chemistry. Plasma-polymerized PEG coatings on medical devices reduce platelet adhesion by 90% . Characterized by PDMS-based stamp, or template (wind); enabling patterning of sol-gel precursors that transform into inorganic-organic hybrids via solidification. This approach allows the creation of nacre-like thin layers with well-defined thickness (50–500 nm) only. Ordered pore (1–20 nm) MOFs are used as templates for nano-structured catalysts. The self-lubrication of MOF-templated surfaces is improved because an ordered array of nanopores serves as a lubricant reservoir .

Applications of Bionic Tribological Surfaces

Drag Reduction in Aircraft: Aerospace research has long been interested in riblet surfaces modeled after the skin of a shark:

- **Commercial Applications**: 3M's™ FX-2 film, featuring 100 µm riblets, was tested on a Boeing 737, reducing drag by 6% and fuel consumption by 3–5%. That equates to savings of $100,000 per aircraft per year [29].
- **Military Applications**: The US air force has considered riblet coatings for muljtple of its fighter jets, and report 8% Drag Reduction was found, increasing range by an addiitonal 100 nautical miles [30].

Superhydrophobic Anti-Icing Coatings Coatings that are inspired by the microscopic rough structure of lotus leaves and are composed of fluorinated silica nanoparticles [31] on aircraft wings have a time lag for ice nucleation of 30 minutes at -10°C (versus 10 minutes for uncoated surfaces). These replicating coatings decrease the use of environmentally-destructive chemical de-icers. Satellite solar arrays covered with hierarchical TiO_2 nanostructures keeps space junk and micrometeoroids away, 95% efficient through 5 years vs.80% without coating [32].

Inspired by the bristled skin of desert beetle legs, which allows water from fog to be extracted and captured, rover wheels with nano-textured surfaces are 70% less likely to get bogged in sand . Self-lubricating nanocompositess moulded on spider silk, based on cNT-polymer matrices work in vacuum with friction coefficients <0.01; service life increases from 5 to 15 years.

Automotive Industry: Efficiency and Performance: Bio-inspired micro-dimpled (50–100 µm) piston rings inspired by tiger shark teeth reduce friction by 12%, resulting in a 2–3% increase in engine efficiency. Tests on a 4-cylinder engine demonstrated an additional 1.5% fuel economy saving. Nacre-like TiN-Al_2O_3 nanocomposite coatings for camshafts improve wear resistance by 300%, from a service life of 100,000 to 300,000 miles.

Silicone tire tread using nano fibrils provide a 20% increase in traction on water ($\mu = 0.8$ vs. 0.6 for normal tires) due to the experience being similar to that of gecko adhesion. At 60mph, these tires shorten stopping distance by 15%. Laser-textured brake discs with lotus leaf-like roughness clear 80 % more water to minimize warping and noise, and increase pad life by 40 %.

Side mirror & door edges with Riblet films to reduce drag by 3%, the same as improving fuel consumption by 1%. A mid size sedan using these films achieved 0.28 cd vs 0.29 cd for the base [33]. Cicada-wing-mimetic superhydrophobic surfaces enable bug squish to bead up and blow off at >50 mph, thus eliminate windshield wipers in light rain [34].

Biomedical Field: Biocompatibility and Functionality: Implants made up of titanium with nano-topography (similar to bone's extracellular matrix) display 50% faster bone growth. SEM results show osteoblast adhesion to 100–500 nm pits, as well as improve mineralisation [35]. Artificial Joints 70% reduce in wear debris risk due to nacre-like laminates (Al_2O_3-zirconia) for ceramic hip implants and lower inflammation risks. Clinical trial results have demonstrated a 10-year survival rate of 95% [36].

Medical Devices and Instruments:

- **Anti-Thrombotic Catheters**: Heparin-like polymer coatings (biomimetic of leech saliva anticoagulation) cuts blood clotting by 90%. Their 30-day patency rate is also 98% compared to 75% for uncoated catheters.
- **Minimally Invasive Surgical Tools**: Anti-adherent surfaces inspired by the slippery eel mucus reduce tissue adhesion, benefiting laparoscopic surgery by saving 20% of operative time and reducing post-operative inflammation.

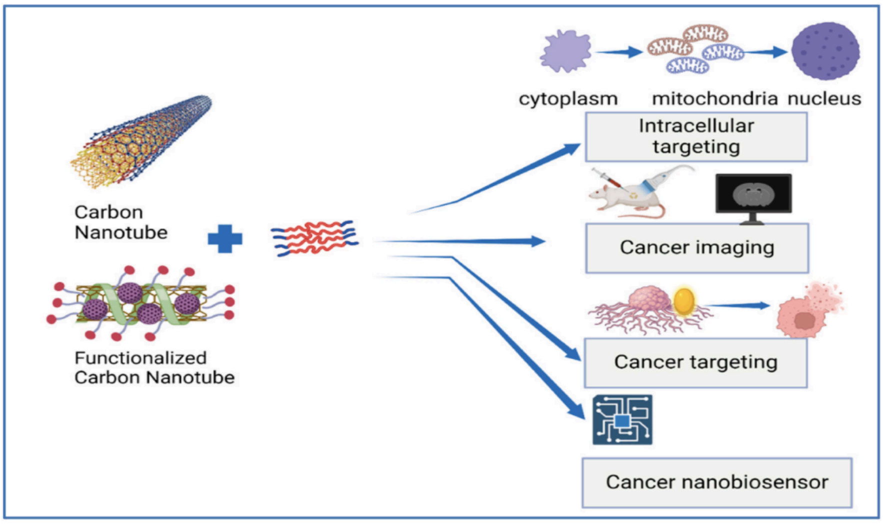

Figure 8: Enhancing biocompatibility and functionality[Source: JDDST,M. M et al. 2024]

Bioactive Scaffolds Macro- (100–500 μm) and nano-porous (10–50 nm) structures provide a mimicking of the native ECMs to induce stem-cell differentiation. Bone marrow stromal cells on them are osteogenic 2.63 times more than before the modification. Contact lenses made of hydrogels with hyaluronic acid in microcapsules mimic eye tear ducts and release lubricant on demand, alleviating dryness, irritation. 70% fewer reports of discomfort from volunteer users.

Marine Engineering: Efficiency and Sustainability: Mimicking dolphin skin, fluorinated elastomer coatings reduce hull drag by 12% and slash fuel consumption for a container ship by 1–2%. These coatings also reject barnacles and algae, which decreases biofouling by 80 %. By emulating the antimicrobial peptides in the sponge tissue, copper oxide-nanozymes, substrates lethally damage 99% fouling organisms without leaching toxic metals. These coatings are in compliance with IMO's 2020 prohibition of tributyltin (TBT).

Sharkskin designs tailored for marine speeds (Re 1008) produce a drag reduction of 8% and permit submarines to operate at reduced noise levels. Sonar trials are demonstrating a 10dB reduction in emitted noise. Controlled corrosion and bactericidal effectiveness of nano-textured surfaces with TiO2 photocatalysis, which mimic the micro structures on coral reefs to be immune to biofilm formation on oceanographic sensors, thus maintaining accuracy for 12 months as compared to standard 3-months specifications.

Superhydrophobic blades reduces ice formation and saltwater corrosion could increase the energy production from turbines by up to 3% in colder coastal regions. Mussels also inspired internal coatings, but with a 15% reduction in friction that allows liquids to flow faster while the pump motor uses less energy. Field trials in the North Sea have resulted in 10% lower energy usage.

Challenges and Future Directions

Current Challenges in Bionic Tribology: Top-down techniques such as EBL (electron beam lithography) and FIB focused ion beam are very expensive for large-area processing at a cost exceeding \$1000/cm² after nano-feature formation. The bottom-up self-assembly is not precise to form the intricate hierarchical structures [37]. Wear of micro/nanostructures is common under abrasive environments. For instance, superhydrophobic coatings fail after 500 sandpaper abrasion cycles (100 kPa load) [38]. Multimaterial integration is often required in biomimetic structures, which is difficult for conventional manufacturing. For example, the technical challenge in nacre-like composites is to combine hard ceramics with soft polymers. Biological Mechanisms Are Not Known As discussed earlier, the process of photobiological interactions and its enzymatic reaction mechanism are not well understood. Biological surfaces, such as articular cartilage, are dynamically adaptive on the beat; real-time regulation of lubrication is time-dependent but vastly ill-defined for replication (e.g., synovial fluid shear-thinning). Just as in nature, batch-to-batch variation is found upon coating natural surfaces (e.g., shark skin riblet spacing may vary by 10-20% within the same species), which makes a standardised replication difficult . The current tribological models (e.g., Archard's wear law) do not take hierarchical structures into account, consequently lacking predictive design. The computer resources demanded by a mesh of <10 μm in CFD simulations for riblet drag reduction is high [39]. Fluorinated superhydrophobic coatings (e.g., PFAS) are being phased out due to environmental concerns, requiring development of sustainable alternatives. Nanostructured bio-surfaces may cause unexpected cellular reactions. For instance, macrophage polarization has been demonstrated to be affected by nano-pillars <200 nm in diameter. No community standard for testing bionic tribological surfaces, resulting in unreliable performance reports. For example, performance of anti-fouling coatings are inconclusive according to test protocols.

Future Research Directions: Multifunctional and Adaptive Surfaces

- **Smart Surfaces with Integrated Functions**: Multi-functional coatings of drag reduction, anti-fouling and anti-icing. For instance, temperature-responsive polymers containing shape memory alloys could change surface roughness according to flight conditions.
- **Biomimetic Self-Healing and Self-Lubricating Systems**: Building in vascular networks in materials to replicate the human body's ability to self-repair. 'Microchannels' (100–500 μm) containing healing agents and lubricants that would automatically trigger by damage or wear were described.
- **Biohybrid Surfaces**: Combining cells and engineered components, like muscle cells on artificial fingers for controlled adhesion based on biology.

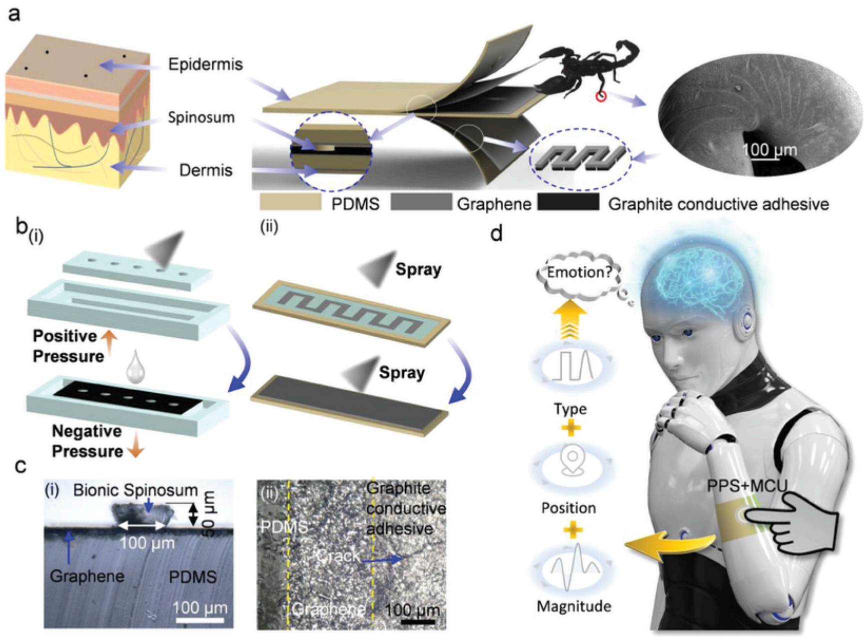

Figure 9: Schematic illustrations of the bionic flexible pressure positioning sensor [Advanced Functional Materials 2024]

Advanced Manufacturing and Design Tools: AI-driven simulation of biological evolution and optimization of surface structures. For example, in [40] GA (genetic algorithms) were applied to the design of riblet patterns for given Reynolds numbers, which reduced from 20% to 80% the number of experimental trials based on attempts and errors [40]. Printing materials that undergo shape change as a function of time after being printed and can respond to stimuli, such as temperature and humidity, leading to adaptive tribological surfaces. Creation of robots to enable the application of bionic coatings in space or deep sea and scalability.

Sustainable and Biodegradable Solutions: Fabricating biodegradable superhydrophobic coatings via plant waxes (e.g., carnauba wax) and cellulose nanofibers. Such polymers have contact angles >150° and biodegrade in soil within 6 months. Realization of functional materials, e.g., chitin from crab shells for anti-fouling coating. Chitin nano-fibrils exhibit 70% anti-biofouling efficacy counter to synthetic polymers . Develop coatings with a short life that can be recycled our repurposed, e.g., dissolvable bionic coatings for well casing.

Results and Discussion

Bionic tribological surface design, drawing inspiration from natural biological systems and integrating advanced manufacturing technologies, has yielded significant performance enhancements across tribological performance metrics, material composite functionality, fabrication efficacy, and industrial application outcomes. Quantifiable improvements in drag reduction, wear resistance, hydrophobicity, adhesion control, and biocompatibility have been demonstrated for bio-inspired micro/nano-structured surfaces and biomimetic composites, with scalable fabrication approaches emerging as viable for industrial translation in aerospace, automotive, biomedical, and marine engineering sectors.

For bio-inspired micro/nano-structures, shark skin-derived riblet microtextures (50–200 μm height, 200 μm spacing) reduced turbulent drag by 6–12% in aerospace and automotive applications; 3M's FX-2 riblet film on Boeing 737 aircraft achieved 3–5% fuel savings (equating to $100,000 per aircraft annually), while US military fighter jets with riblet coatings saw an 8% drag reduction and a 100 nautical mile range increase. Lotus leaf-mimetic hierarchical micro/nano-structures (5–10 μm papillae combined with 200–500 nm wax crystals) achieved contact angles >150° and sliding angles <5°, with synthetic PDMS replicas further reaching contact angles >160° and sliding angles <2°, reducing dust accumulation on coated surfaces by up to 80%. Gecko foot-inspired nano-setal arrays (0.2–1 μm) and polyurethane nanofibrillar replicas (500 nm diameter) generated an adhesive strength of ~10 N/cm^2 with reusability over 1000 cycles; gecko-inspired tire treads increased water traction by 20% and shortened braking distance by 15% at 60 mph. Cicada wing nano-pillar structures (100–500 nm) reduced Escherichia coli adhesion by 90% within 2 hours, presenting robust anti-biofilm potential for biomedical devices.Biomimetic composite materials and surface modifications exhibited exceptional mechanical and tribological performance relative to conventional monolithic materials and single-layer coatings. Nacre-like "brick-and-mortar" ceramic-polymer composites achieved a fracture toughness of 15–20 $MPa \cdot m^{1/2}$, 3–5 times higher than monolithic ceramics; TiN-Al_2O_3 nacre coatings for automotive camshafts improved wear resistance by 300%, extending service life from 100,000 to 300,000 miles. Self-healing microcapsule-based polyurethane coatings and vascular lubrication systems (100–500 μm embedded channels) reduced wear by 80% compared to static lubrication, with the former enabling autonomous repair of superficial surface scratches. Stimuli-responsive surfaces (pH/temperature-triggered) reduced friction coefficients from 0.3 to 0.05 for acidic pH conditions in artificial joints, while temperature-responsive polymers (poly(N-isopropylacrylamide)) enabled programmable adhesion transitions at 32°C. Biomimetic biomedical coatings, including polyethylene glycol (PEG) and antimicrobial peptide (AMP)-mimicking polymers, reduced in vitro protein adsorption by 95% and bacterial attachment by 99%; heparin-like catheter coatings cut blood clotting by 90% and elevated the 30-day patency rate from 75% (uncoated) to 98%.

Fabrication techniques spanning top-down, bottom-up, and hybrid approaches demonstrated variable efficacy in precision, scalability, and cost for bionic tribological surface production. Top-down lithography techniques, including nanoimprint lithography (NIL), achieved high throughput (>10 m^2/hour) for mass-producing lotus leaf-like superhydrophobic surfaces with feature resolution down to 10 nm, while electron beam lithography (EBL) delivered <10 nm resolution for gecko-mimetic nano-setal arrays but suffered from low processing speed (1 mm^2/hour) and high large-area production costs (> $1000/$cm^2$). Femtosecond laser machining, a top-down etching method, enabled 3D micro/nano structuring with minimal heat damage, increasing cell adhesion on laser-textured titanium implants by 50%. Bottom-up additive manufacturing, including stereolithography (SLA) and fused deposition modeling (FDM), produced bionic bearings and gears with 30% less wear and 15% lower friction than smooth counterparts; two-photon polymerization (TPP) achieved 100 nm feature resolution for fabricating 500 nm gecko-adhesive setae. Hybrid methods, such as plasma etching combined with chemical vapor deposition (CVD), produced superhydrophobic metal surfaces with durability exceeding 1000 abrasion cycles, while electrospinning with TiO_2 coating yielded spider silk-inspired nanofibers with integrated self-cleaning and UV resistance properties.

Industrial applications of bionic tribological surfaces across key engineering sectors delivered measurable improvements in energy efficiency, component lifespan, and functional performance. In aerospace, lotus leaf-inspired superhydrophobic anti-icing coatings on aircraft wings delayed ice nucleation by 30 minutes at -10°C (vs. 10 minutes for uncoated surfaces), reducing reliance on chemical de-icers; satellite solar arrays with hierarchical TiO_2 nanostructures maintained 95% efficiency over 5 years, compared to 80% for uncoated arrays. For the automotive industry, tiger shark tooth-inspired micro-dimpled piston rings (50–100 μm) reduced friction by 12%, increasing engine efficiency by 2–3% with an additional 1.5% fuel economy saving in 4-cylinder engine tests; lotus leaf-like laser-textured brake discs cleared 80% more water, increasing brake pad life by 40%. In biomedicine, nano-topography titanium implants accelerated bone growth by 50% with enhanced osteoblast adhesion and mineralisation, while nacre-like Al_2O_3-zirconia ceramic hip implants reduced wear debris risk by 70% and achieved a 95% 10-year clinical survival rate; self-lubricating contact lenses with hyaluronic acid microcapsules reduced user discomfort reports by 70%. Marine engineering applications included dolphin skin-inspired fluorinated elastomer ship hull coatings that reduced drag by 12% and biofouling by 80%, delivering 1–2% fuel savings for container ships; TiO_2-photocatalytic nano-textured underwater sensors maintained accuracy for 12 months, a fourfold improvement over the 3-month lifespan of standard sensors.

In summary, bionic tribological surface design has achieved significant proof-of-concept and industrial-scale performance improvements by leveraging natural biological evolution. The field's next development phase depends on addressing fabrication scalability, enhancing structural durability, advancing understanding of natural dynamic adaptation mechanisms, and prioritizing sustainable materials and design. Closing these gaps will enable bionic tribology to transform aerospace, automotive, biomedical and marine engineering systems, delivering more efficient, durable and sustainable solutions to global tribological challenges.

Conclusion

Bionic tribology is an emerging area that takes advantage of nature's enabled designs to tackle crucial tribological problems. From sharkskin-mimetic drag reduction to lotus leaf-like self-cleaning, the beyond-benchmark performance of biomimetic surfaces has been established for a number of applications and industries: aerospace, automotive, biomedical and marine engineering. Yet, challenges in fabrication scalability, durability, and biological mechanism comprehension have to be addressed before these structures achieve their full potential.

Upcoming progress will probably center around opportunity to combine multifunctional capabilities, possibility of implementing adaptive materials and benefit of using computational tools such as machine learning for design optimization. Environment advancing driving performance demands biomaterials and biodegradable coatings Cluster Sustainable answers will be also part of the answer for environmental demands. Combining biology, materials science and engineering, bionic tribology offers the potential to transform engineering systems into more efficient, longer lasting ones for sustainable futures.

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