A Materials and Energy Balance of Bio-Mimic Tribology

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Abstract

Bio-inspired tribology is viable for the synchronization of materials-energy balance at TRIBO interface. Adhesion, lubrication, and wear control of the biomechanical domain carried scientific innovation for the promotion of sustainability. One-third share of high-grade fuel energy is lost at tribological contacts globally by mechanical machinery in the generation of mechanical work. Environmental loading of carbon created an academic inertia during SARS-CoV-2 pandemic outbreak or post-pandemic zone for re-searching at bio-inspired tribology. Academic content is a heterogeneous expression of adsorption, friction, and energy optimization over engineering surfaces.

Keywords: Supramolecular interaction; Adsorption; COF; Synovial lubrication; Nanoparticles; Stick-slip friction

1. Introduction

1.1. Adhesion

Mechanical interlocking, adsorption, diffusion, capillary action, electrostatic forces, hydrophobic association, Vander Walls, and π-π interaction resolve the complexities of adhesion at bioengineering interfaces in the micro-nano spectrum.[1] Nature exhibits unique adhesive properties of biological '*hydrophilic/hydrophobic*' surfaces after billion years of evolution. Exploration of underlying adhesion mechanisms in mathematical peeling models 1944 onwards is summarized with Kendall peeling model 1975 or 'Tape model' as a function of elasticity and adhesion energy.[2-4] Mechanical interlocking is an intrinsic adhesion of irregular substrate interface by the third bodies in irregularity viable in explaining a part of cellulose fiber/thermoset and thermoplastic matrix perfect bonding. Adsorption of adhesive molecules over substrate contributes to friction in tribological systems. Diffusion is a movement of molecules from high concentration to low concentration valuable in explanation of ultra-low boundary lubrication of synovial fluid. Supramolecular interaction is a non-negligible force for understanding of intrinsic molecular assembly from non-covalent bonding.

1.2 Friction

Leonardo da Vinci laws of sliding friction (1493) motivated pioneer tribologists century to century for investigations of complexities of frictional behavior encountered in engineering applications to nanotechnology.[5-6] Two centuries later Amontons´ law of friction states; the ratio of friction force to normal load is 'coefficient of friction' and independent of normal load or apparent interfacial area.[7] Coulomb's law of friction states dependence of interfacial friction on normal load, independent on apparent area of contact, independent of interfacial velocity. Friction models useful in metal forming processes including 'Bowden and Tabor' presented in second half of twentieth century reinforced rheology of real area of contact of mixed lubrication regime incorporated with other complex frictional models.[8] Tribology is natural phenomenon seen in human life from nano scale, biological lubrication in boundary regime, to macro scale up to earthquake. Stribeck curve trifurcates fluid-film frictional behavior of real interfaces having relative motion in boundary lubrication, mixed lubrication, and hydrodynamic lubrication regimes with operating parameters. Friction is not an inherent property of interfacial materials and depends on external factors i.e., moisture, pressure, relative speed, real area of contact, temperature in addition of materials properties.

1.3 Stick-slip mechanism

The prevalence of static friction in ultrahigh vacuum at pure crystalline interface is theoretically null and existence of friction by third bodies molecules such as hydrocarbons or carbon dots absorb on any surface responsible for mechanical interlocking or interfacial friction stress.[9] Prandtl-Tomlinson model is popular for stick-slip nanotribology by dragging nanoparticle with spring/damper in periodic potential described in basic equation of motion.

$$m\ddot{x} + c\dot{x} + k(x - vt) = F_0 \sin\,(2\pi x/a) \qquad \text{(i)}$$

Where, 'x' is coordinate of nanoparticle, 'm' an oscillatory mass attached with spring damper, 'c' damping coefficient, 'k' spring stiffness, 'F_0' the amplitude of periodic force, and 'a' the spatial period of potential.[10-11] Velocity dependence of coefficient of friction in local density of real contact area by breaking down of Amontons′ law from a quasi-static precursor appearing in stick-slip to dynamic precursor included in form of state dependant friction law.

2. Carbon allotropes

2.1 Diamond and amorphous carbon

Crystallographic structure of '*Diamond*' is face centred cubic pattern of eight carbon atoms unit cell with atomic packing factor (~0.34) in robust sp^3 hybridisation.[13] The hardest known minerals, high dispersion of light, precious economy, and industrial applications relocate carbon allotrope in ultra-perspective. Diamond like carbon (DLC) is carbon amorphous in sp^3 hybridised form with '*hydrophobic*' characteristics provides TRIBO performance in engineering robust coatings. Coal is amorphous of carbon economically viable in India from eighteen century onwards in advancement of transport and energy sector viz. ~0.2 TW of coal-based electricity production with ~53 percent of power sector quantitative electricity share in 2K20. Coal tar carried innovation in biomedical and engineering applications.[14-15] Diamond and amorphous carbon carried economic values for tribological functionalisation in precious '*Jems & Jewellery*' and other applications.

2.2 Graphene based nanoparticles

'Graphite' crystallographic structure is hexagonal close-packed with atomic packing factor (~0.74) in the sp^2 hybridisation thermodynamically stable state of low-cost mineral. Mechanical and electrical superb performance of graphite promoted innovation in engineering applications.[16-17] Free standing monolayer sp^2 hybridised honeycomb lattice (~0.9 nm thickness) of '*Graphene*' is hydrophobic with superlative performance in nanotechnology.[18] A true aromatic macromolecule is basic building block in wrapping of 0D carbon dots, uniaxial carbon nanotube, and 3-D graphite with supramolecular interactions. Graphene oxide (GO) is a honeycomb lattice with sp^2 and sp^3 hybridized carbon atoms in presence of hydroxyl functional groups (-OH) and carboxyl functional groups (-COOH). Biofunctionalization of graphene-based nanocomposites (GBN) is synergistic in biosensors/biomedical non-covalent adsorption performance.[19] Biomechanical adhesion from functional groups is shown in useful for engineering and biomedical applications.

2.3 Fullerenes/CNT

Fullerene is a cage like structure of carbon atoms popularly known as Buckminsterfullerne (C_{60}), buckyballs or zero-dimensional (0D) nanoparticle- a truncated icosahedron structured of sixty carbon atoms with twenty hexagons and twelve pentagons.[20-22] C_{70} fullerene consisting of seventy carbon atoms, twenty-five hexagons, and twelve pentagons. Rolling graphene sheets in cylindrical shape capped with half fullerene is termed carbon nano tube (CNT). Intrinsic hydrophobic, electrically conductive, robust mechanical strengths, relatively more surface area than other carbon-based nanomaterials, and classified into single-wall carbon nano tubes (SWCNT) or multi-wall carbon nano tubes (MWCNT).[23-24] Carbon aerogels are nanostructured carbons with relatively high porosity, super electricity conductions in electo(catalysis), and large surface area. Synthesis of carbon aerogel by polycondensation of resornicol and formaldehyde, sol-gel polycondensation, and pyrolysis/carbonisation for extraction of non-carbon entities. Carbon gels innovative applications in energy storage, catalytic scallolds, adsorbents, organic pollutant separators, and thermal insulators.[25-26]

3. Natural fiber composites

3.1 Life cycle assessment

Cellulose is the most abundant biopolymer (DP 1000-10,000) found over planet having three hydroxyl functional groups with monomer for formation of hydrogen bond in crystalline region. Cellulose is diffused in photosynthesis for a balance of carbon cycle, water cycle, climate action, and life on land. '*Hydrophilic*' cellulose and '*Hydrophobic*' lignin form a natural raw composite with pectin/hemi-cellulose in diversity of biology. Ultra-specific properties, biocompatible, non-toxic nature of cellulose promotes *in situ* life cycle assessment for durability in sustainable pattern of human life. Advancement of low carbon materials in applications and promotion of sustainability to mend relationship of mankind with ecology have been reviewed on the life cycle assessment of cellulose.[27]

3.2 Wear

Sugarcane fiber reinforced thermosets polymer tested for adhesive wear resistance in parallel orientation and antiparallel orientation of fibers with favorable natural fiber/polyester matrix bonding.[28] The abrasive wear of '*Phyllostachys pubescens'* stem is investigated in mixture of 96.5 wt.% quartz sand, 3.5 wt. % bentonite powder, 3.0 wt. % water, and concluded that the abrasive wear resistance a function of vascular fiber content, the abrasive particle size, and the relative sliding velocity.[29] Adequate toughness in moderate impact of bamboo biocomposites used in fabrication of super-mileage low cost vehicle frame using '*Rule of Mixture*' with assumption of perfect bonding at fiber/matrix interface and equal strains provides upper bound solution.[30] Rule of mixture is weighted mean to predict mechanical properties included herein;

$$E_c = fE_f + (1 - f)E_m \quad \text{(ii)}$$

Where, 'f' is volume fraction of fiber, 'E_c', 'E_f' and 'E_m' are elastic modulus of composite/fiber/matrix

Lignin is a hydrophobic macromolecule of water reservoir in plants assumed to be bonded with cellulose, pectin, and hemicellulose by mechanical interlinking and supramolecular interaction rather than covalent bonding for resolving complexities of natural adhesion under nature consciousness.[31]

Table A Mechanical properties of bio-inspired materials

S. No	Biopolymers	Elastic moduli (GPa)	Strength (MPa)	Failure strain (%)	Ref.,
A#1	Nanocellulose (% cellulose 88.8±0.9)	60.2±0.8	1014.7±69.1	#DP 1944±44.2	[32]
A#2	Sisal fiber	18.7±3.1	681±58	2.0 - 2.5	[33]
A#3	CNF-g-PEG	32.3±5.7	576±54	-	[34]
A#4	NFC-GO	~34.1	~442.4	~2.0	[35]
A#5	PLLA	~1.81	~40	~3.3	[36]

DP; Degree of polymerization

Table B Coefficient of friction in an engineering spectrum

S. No	TRIBO indicators	Coefficient of friction	Ref.,
B#1	Basalt/Jute fibers, polyester/vinyl-based thermoset matrix, and PTFE/POM/MoS_2 tribo-fillers	0.22 - 0.74	[37]
B#2	Biocomposites polished interface under water nanofilm ~70 nm from ultra-low viscosity of water	0.06 – 0.08	[38]
B#3	Adhesion and friction at multilayer molecular layer of lubricants for nanotribology	0.018 – 0.030	[39]
B#4	Diamond-like carbon coating under oleic acid lubrication, Graphene oxide formation	0.04 – 0.10	[40]
B#5	Abrasive and graphite, sintered metallic friction materials, and wear rate	0.31 – 0.45	[41]

4. Synovial lubrication

4.1 Biology

Biological lubrication at articulating cartilage is governed by lubricin, hyaluronic acid (HA), and extracellular matrix of cartilage from TRIBO perspective. Lubricin/glycoprotein/PRG4 is diffused across synovial membrane by cellular metabolism and coat superficial zone for a boundary lubrication with molecular weight of lubricin (230-280 kDa) having amino/carboxyl functional groups.[42] Surface active biomolecules in synovial lubricant responsible for ultra-low coefficient of friction included such as PRG4 (0.05-0.35 mg/mL), HA (1-4 mg/mL), phospholipids (0.1 mg/mL), among others for healthy articulation.[43] Hyaluronic acid (HA) is a polysaccharide inherently protects cartilage in elevated conditions (~20 MPa) and HA digested cartilage lower down molecular weight upto 0.5MDa in stick-slip domain by mechanical interlinking of cartilage interface with constricted collagen network.[44] Cartilage is a viscoelastic tissue of extracellular matrix for bearing of mechanical load with chondrocytes for regeneration of extracellular matrix in biomechanical integrity of cartilage.[45] Lubricin binds and regulate immune receptors in stick-slip domain for preventing cartilage-cartilage adsorption.[46] A fundamental understanding of biology at articulating cartilage is viable for virtual investigation of tribology from mechanical indicators.

4.2 Biomechanics

The mechanical load at articulating interface is enshrined ~4 times of body weight in gait, ~8 times of body weight in stumbling, and ~5.5 times of body weight in fast jogging.[47] Stribeck curve is illustrated independently for lubricin and HA in boundary lubrication, mixed lubrication, and hydrodynamic lubrication for separation of tribological performance of boundary lubricant macromolecules in operating conditions.[48] Diffusion coefficient across inhomogeneous and anisotropic tissues is predicted by Fick's law of diffusion for bovine serum albumin (66 kDa) in finite element simulation.[49] The quantitative biomechanical investigations elucidated for tensile modulus (~0.65 MPa for repaired tissues and ~5.2 MPa for intact contact) and integration strengths (~1.2 MPa for repaired tissues and ~2.7 MPa for intact contact) to restore mechanical properties of cartilage tissues.[50] A shear-thinning viscosity model is included for synovial lubricant in consideration of concentration of HA and shear rate that fundamentally belonging to power law.[51]

$$\mu = \mu_0 e^{\alpha c}[1 + \gamma |D|^2]^n \qquad \text{(iii)}$$

Where, *a, c, n, γ* are constants determined experimentally and *D* stands for velocity gradient across lubricating layer

Table C Coefficient of friction for synovial lubrication/model SF

S. No	TRIBO indicators	Coefficient of friction	Ref.,
C#1	Phosphatidylcholine liposomes ultra-low friction performance in boundary lubrication regime	2E-5 – 6E-4	[52]
C#2	Cartilage-cartilage synovial ultra-low friction in boundary lubrication	0.0005 – 0.04	[53]
C#3	Glycoprotein in buffered saline solution at interface of hydrophilic negatively charged mica	0.020 – 0.056	[54]
C#4	Cartilage-CoCrMo testing at physiological sliding velocities with shear thinning bio-lubricant	0.012 - 0.058	[55]
C#5	Alumina femoral head at UHMWPE dimpled acetabular cup with smooth cup by model SF	0.171 – 0.285	[56]

5. Skin friction

5.1 Air lubrication

A combination of mass density and kinematic viscosity of air is lesser than water in formation of boundary layer over streamline body. Air lubrication is used by scientific fraternity in designing of mechanical machineries for reduction of skin drag by air pumping over tribological surface.[57] Emperor penguins extraordinary friction stress reducing efficacy in water by air injection for achievement of high under water speed is summarized for restoring/release air in their plumage/feathers. Emperor penguins achieve equitable speed in ascending due to air lubrication, reducing frictional drag, a part of transformation in buoyancy force, and cavitation is avoided in bobble formation.[58]

5.2 Skin-friction drag

The drag power experience by 'Dolphin' is larger than estimated muscle power reported in 1936 by British zoologist Sir James Gray-termed as Gray's paradox. A fluid mechanical perspective of paradox is summarized in view point that swimmer spend muscle power to overcome drag power in undulatory swimming.[59] The muscle energy is expended to generate lateral undulations of the swimmer body and the drag power is balanced by thrust power not by muscle power. The muscle power is dissipated in deformation kinematics of biodiversity in water and balanced not by muscle power inherently by thrust power. Author perspective for swimmers and 'Dolphin' has inverse regression of muscle power and drag power with respect to diversity of biology as *de facto* existence of upper bound net mechanical efficiency-a ratio of mechanical work to expended energy above resting. Friction stress over streamline body is predicted by the relation as strong function of velocity with boundary layer.

$$\tau_f = 0.5 C_d \rho V^2 \tag{iv}$$

Where, C_d is drag coefficient a function of Reynolds number for laminar and turbulent boundary layers[60] listed

6. Adsorption case study

Cooking fumes generation from vegetable oils in household applications such as aerosols of fat with small aerodynamic size (50-500 nm), polycyclic aromatic hydrocarbons, heterocyclic compounds, anthropogenic particulate matter ($PM_{2.5}$), and air borne syndrome SARS-CoV-2 in general trapped at stick-slip TRIBO surfaces. Transient adsorption of nanoparticles/microparticles over kitchen exhaust fan air propeller blades included in brief for reinforcement of originality in academic remedy. A little environmental loading from carbon footprint in limited quantity or cytotoxicity for adhesion/adsorption implicitly secure performance indicators in urban cities for good health and well-being.

Conclusions

Biomimetics presented with academic content is a cohort perspective of adhesion, friction, lubrication, and wear in biomechanical applications viable for fundamental understanding of TRIBO interface enshrined in Table A, Table B, and Table C for rendering of academic content.

- Friction is a function of state variables
- DLC coating is equivalent to few-layers graphene oxide in presence of a little functional groups over coat
- Stick-slip friction at articulating cartilage is dependent on mechanical static loading
- Gray's paradox is introspectively in diversity of biology lens for prediction of drag power and muscle power
- Lubricin bind and regulate immune receptors for synergistic mechanical efficiency

Author included a case study of adsorption of tribological aerosol fat over kitchen exhaust fan blade in investigation of *in situ* third party hydrocarbons formation from academic innovation. Contribution of friction in daily life is quoted for protection of human life and personal liberty for achievement of human performance indicators.

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Conflict of Interests

Achievement of academic performance indicators safeguarded by UGC to university faculty is primary perception of author profoundly none competing interest from residual indicators

Author contribution

Author wrote paper for achievement of academic performance indicators

Ethics declaration

Academic content is a personal viewpoint for realization of sustainability from bionic interfaces

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