Frictional Behavior of (PEI/GO)x Solid Lubricant Coatings on Steel Substrates in Various Environments

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What is Graphene & Related Materials?

- **Graphene**: A single layer originated (separated) from graphite.
- **Graphite Oxide**: An oxidized product of graphite with > 8 layers.
- **Graphene Oxide**: An oxidized product of graphite with < 8 layers.
- **Reduced Graphene Oxide**: Reduced product of Graphene Oxide.

Motivation

- To obtain more clear understanding on tribology of graphene and related materials under various environments.
- To develop a simple and feasible coating for real-time applications.
- To develop graphene oxide based coatings because good bonding with any substrate.
- To conduct more detailed investigation on molecular scale frictional behavior using simulations.
Electrostatic self assembly / layer by layer (LbL)

Substrate: Polished 440C steel discs - 56 mm × 3 mm

O₂ plasma surface activation

Non-coated disc

Immersion into the polycation solution
0.2 wt% polyethyleneimine (PEI)

15 min

Washing in DI H₂O
Drying in air

Immersion into the anionic compound solution
0.1 wt% graphene oxide (GO)

Coating design and characterization by Roman Selyanchyn

Collaborative research with CCU division (PI: Prof. S. Fujikawa)

Washing in DI H₂O
Drying in air

(PEI/GO)₅ coated disc
Surface Morphology

(PEI/GO)$_n$ coating thicknesses shown by cross-sectional SEM images

Uncoated (PEI/GO)$_5$ (PEI/GO)$_{10}$ (PEI/GO)$_{15}$
Tribological Characterization (Humid air and Vacuum)

**Ambient air**
- All \((\text{PEI/GO})_n\) LbL coatings showed the same COF \(\approx 0.2\)
- Different wear lives were exhibited.

**Vacuum**
- Non-coated disk (bare) and \((\text{PEI/GO})_5\) LbL coating showed the high COF and low wear life.
- \((\text{PEI/GO})_{10\&15}\) LbL coatings showed the low COF and similar wear life
Tribological Characterization (Dry H₂ and N₂)

Stepping from low friction to high friction

Dry H₂
Bare steel
(PEI/GO)₅
(PEI/GO)₁₀
(PEI/GO)₁₅

Coefficient of friction, COF (µ)
Number of sliding cycles (N)

Dry N₂
Bare steel
(PEI/GO)₅
(PEI/GO)₁₀
(PEI/GO)₁₅

Coefficient of friction, COF (µ)
Number of sliding cycles (N)
Summary of Tribology Results

- **Uncoated Disk**
- **(PEI/GO)5**
- **(PEI/GO)10**
- **(PEI/GO)15**

**Steady-state coefficient of friction, COF (μ)**

Environments:
- Humid air
- Vacuum
- Hydrogen
- Nitrogen

Graphene COF from literature
Tribological behavior in humid atmosphere

PEI polymer
Graphene oxide layers
Steel ball
Wear debris
Water molecules

Substrate: steel, glass, silicon wafer

µm
Tribological behavior in dry atmosphere (H₂, N₂ and Vacuum)

- PEI polymer
- Steel ball
- Graphene oxide layers
- Wear debris
- H₂ and N₂ molecules

Substrate: steel, glass, silicon wafer

Scale markers: nm, μm
Graphene oxide layers
Water molecules

Atmosphere
PEI polymer

Normal air

SEM Images

TEM Images

Dry H₂

Dry N₂

Ref: Chem. Commun., 2011, 47, 12370-12372
Conclusions

- Steady-state friction coefficients were reduced by: **dry H\textsubscript{2} \sim 14** and **dry N\textsubscript{2} \sim 29**.
- A strong influence of environments (i.e., moisture and dry) on friction behavior of (PEI/GO\textsubscript{n}) have been observed.
- Higher thickness coatings ((PEI/GO\textsubscript{10&15}) has superior tribology than thin (PEI/GO\textsubscript{5}) bi-layer.
- The moisture in ambient air has restricted the graphene oxide flakes to form an easy rolling configuration (nanoshells).
- Dry environments promote the formation of scroll like configuration which indeed reduced the friction to least values (COF \sim 0.02).
- Dry hydrogen intercalated with oxygen groups of GO to form water, which affects the sliding behavior of GO.