Tribological behaviour of carbon filled hybrid UHMWPE composites in water

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Introduction
Move towards water lubrication

• Water a better option than EALs (Environmentally Adapted Lubricants)
  • Non toxic, readily available (especially in aqueous envt.)

• Use of water as lubricant requires use of special materials for shafts, bearing, etc.
  • Prevalence of boundary lubrication

http://www.w-program.nu/filer/exjobb/Stina_%C3%A5strand.pdf
Introduction
Polymer Based Materials (PBMs)

• PBMs are good candidates for use in boundary lubricated conditions [1-3]
  – Thermoplastics
  – Can follow the substrate deformations
  – Self-lubricating property
  – PLA, PPS, PE, etc.

• Drawbacks
  – Viscoelastic deformation, water absorption
  – High wear rates

Improvement pathways

- Carbon based
  - CNTs
  - Graphene
- Metal particles
- Fibers

Process:
- Cross linking by radiation
- Fillers/composites
- Improvement pathways
- Vitamin E
- Polymer Blending
Hybrid/Multiscale Composites

• Combine both micro and nano reinforcements
  – Ability to functionalize the fillers, Possibility to tailor properties, synergistic effect.

• Micro and nano HA in UHMWPE combine to give better mechanical properties than either of them alone [10]


UHMWPE
Ultra High Molecular weight Polyethylene

• Semi crystalline thermoplastic polymer with Molecular weight usually between 2 and 6 million g/mol
  • High molecular weight imparts toughness

• Superior performance in load bearing systems where water and non oil based lubrication is used [4,5] and also in biomedical applications [7,8]

• Excellent low-speed performance of Rubber/UHMWPE alloy as material for marine stern tube bearings[6]

Research objectives

1. To design Multiscale composites based on UHMWPE
2. To experimentally investigate the synergistic effect of fillers on tribological performance and properties
### Materials

<table>
<thead>
<tr>
<th>Particle</th>
<th>Average size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene Oxide (GO)</td>
<td>Length/width 0.7 – 4 μm, Profile 0.7-1.2 nm</td>
</tr>
<tr>
<td>Nanodiamonds (ND)</td>
<td>Ø 5 nm</td>
</tr>
<tr>
<td>Short Carbon Fibers (SCF)</td>
<td>length 100 μm, Ø 7 μm</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>Ø 30 μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Designation</th>
<th>Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GO</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>Pure UHMWPE</td>
</tr>
<tr>
<td>0.5% GO</td>
<td>0.5</td>
</tr>
<tr>
<td>0.5% ND</td>
<td>-</td>
</tr>
<tr>
<td>10% SCF</td>
<td>-</td>
</tr>
<tr>
<td>GO + ND + SCF</td>
<td>0.5</td>
</tr>
<tr>
<td>GO + ND</td>
<td>0.5</td>
</tr>
<tr>
<td>GO + SCF</td>
<td>0.5</td>
</tr>
<tr>
<td>ND + SCF</td>
<td>-</td>
</tr>
<tr>
<td>1% GO</td>
<td>1</td>
</tr>
<tr>
<td>1% ND</td>
<td>-</td>
</tr>
</tbody>
</table>

Chukov et al., Investigation of structure, mechanical and tribological properties of short carbon fiber reinforced UHMWPE-matrix composites, Composites Part B: Engineering, 76, 79-88, 2015
Manufacturing Process

Sonication in ethanol → UHMWPE + Filler → Ball Milling Dry/wet → Composite powder → Direct Compression Molding → Drying

Measurements and analyses

- Pin on disc tribo tests
  - Time: 20h
  - Sliding distance ~ 9400 m
  - Counter Surface: Inconel 625 discs
  - Load: 88 N
  - Contact pressure – 5 MPa
- SEM
- Wettability
- Thermal characterisation
  - DSC
  - TGA

![Diagram](image-url)
SEM

Unfilled UHMWPE-pre milling

Unfilled UHMWPE-post milling

GO + ND + SCF
Post milling
X ray Microtomography
• Reduction of $\mu$ with addition of GO and ND

• 140 $\mu$m PE + GO/ND showed higher FC [14,15]

• GO+ND+SCF displays low $\mu$
  – 21% reduction compared to unfilled UHMWPE

Specific wear rate (SWR) of polymer composites

- Even though 10% SCF shows high $\mu$, wear rate is not - SCF can protect the polymer from abrasion.

- Low value of GO+ND+SCF – 15% decrease from unfilled UHMWPE

- 140 $\mu$m UHMWPE+GO has higher wear rate [14]

Wear tracks

GO+UHMWPE

SCF+UHMWPE

ND+UHMWPE

GO + ND + SCF + UHMWPE
Wettability

- Hydrophobicity of UHMWPE is an important factor in low wear rate in metal-on-polymer contacts [19]
- All fillers used tend to increase hydrophobicity
- 11% increase in contact angle for GO+ND+SCF

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Sample</th>
<th>Mean Contact angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pure UHMWPE</td>
<td>81.4</td>
</tr>
<tr>
<td>2</td>
<td>0.5 wt% GO</td>
<td>82.6</td>
</tr>
<tr>
<td>3</td>
<td>1 wt% GO</td>
<td>85.9</td>
</tr>
<tr>
<td>4</td>
<td>0.5 wt% ND</td>
<td>89.3</td>
</tr>
<tr>
<td>5</td>
<td>1 wt% ND</td>
<td>86.8</td>
</tr>
<tr>
<td>6</td>
<td>10 wt% SCF</td>
<td>88.3</td>
</tr>
<tr>
<td>7</td>
<td>GO + ND + SCF</td>
<td>90.1</td>
</tr>
<tr>
<td>8</td>
<td>GO + ND</td>
<td>88</td>
</tr>
<tr>
<td>9</td>
<td>GO + SCF</td>
<td>90.4</td>
</tr>
<tr>
<td>10</td>
<td>ND + SCF</td>
<td>89.5</td>
</tr>
</tbody>
</table>

Contact angle vs. $\mu$

- Higher the contact angle, lower the $\mu$ – as desired.
- GO+ND+SCF exhibits low wear and lowest $\mu$ with good hydrophobic nature.
Differential Scanning Calorimetry

• Crystallinity not affected by manufacturing process

• Similarly, no effect on melting point

• Note: Crystallinity was improved with the addition of small amount of GO and ND – act as nucleation centers [22,23]

• SCF inhibits chain formation[17]

Enqvist et al., Nanodiamond reinforced uhmwpe: a comparison of dry and wet ball milling manufacturing, Tribology - Materials, Surfaces & Interfaces Volume 8, Issue 1, 2014
Thermo-gravimetric analysis

Thermal stability of polymers

<table>
<thead>
<tr>
<th>Weight left</th>
<th>Label</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 %</td>
<td>T0</td>
<td>point just before any temperature changes start to occur</td>
</tr>
<tr>
<td>95 %</td>
<td>T1</td>
<td>temperature for maximum sample mass</td>
</tr>
<tr>
<td>90%</td>
<td>T2</td>
<td>end of the gradual weight loss</td>
</tr>
<tr>
<td>5%</td>
<td>T3</td>
<td>rapid degradation ends</td>
</tr>
<tr>
<td>≤ 1%</td>
<td>T4</td>
<td>sample has achieved complete decomposition</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composite</th>
<th>Temperature (°C) ± Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T0</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>167±5.5</td>
</tr>
<tr>
<td>GO+ND+SCF</td>
<td>210±2.4</td>
</tr>
</tbody>
</table>

- Composite GO+ND+SCF has the most delayed temperature points
- Delayed oxidation and consequent degradation [18]

Concluding remarks

- Manufacturing process has been optimized.
- Use of smaller PE particles has a positive influence on performance and properties.
- Inclusion of fillers did not affect crystallinity.
- Thermal stability of polymer composites was improved.
- Hybrid composite has been prepared and shown to perform well. GO+ND+SCF has
  - good hydrophobic nature - 11% increase
  - low $\mu$ - 21% less than unfilled UHMWPE
  - low wear - 15% reduction compared to unfilled UHMWPE
Thank you
Contact: hari.vadivel@ltu.se
Luleå University of Technology

This project was carried out within TRIBOS master (European Master MSc. degree in tribology)
# References


6. Hong-ling Qin, Xin-cong Zhou, Xin-ze Zhao, Jing-tang Xing, Zhi-ming Yan, A new rubber/UHMWPE alloy for water-lubricated stern bearings, Wear, Volume 328, 2015, Pages 257-261, ISSN 0043-1648,


11. Berman et al., 2015, Macroscale superlubricity enabled by graphene nanoscroll formation, Research, Vol 348 Issue 6239


16. Enqvist et al., Nanodiamond reinforced uhmwpe: a comparison of dry and wet ball milling manufacturing, Tribology - Materials, Surfaces & Interfaces Volume 8, Issue 1, 2014


