Structuring of Nanoparticles Using Oscillating Magnetic Fields

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Summary

Nanoparticles (carbon, ceramic, metal, etc.), when implemented as ordered micro-structures, can enhance mechanical, thermal, electrical, and other multi-functional properties of polymer nanocomposites. Currently, however, nanocomposites with ordered micro-structures cannot be fabricated in large size, and thus application of these novel nanocomposites in bulk has stagnated. Our goal is to develop a scalable capability to actively assemble nanoparticles throughout polymer matrices using oscillating magnetic fields. We take a two-step approach:

1. Preparation of nanoparticles with magnetic anisotropy by coating carbon nanotubes (CNTs) with thin ferromagnetic (Ni) layers.
2. Parametric studies of nanoparticle movements/organization in polymer matrices under oscillating magnetic fields.

If successful, this study will enable and accelerate design and delivery of bulk nanocomposites for aerospace and other applications, and can advance multi-scale structure-processing-property relationship studies.

1. Preparation of Ferromagnetic CNTs

   Chemical Vapor Deposition of Multi-walled CNTs:
   - Diameter ~20 nm, Length ~300 microns
   - Pre-conditioning with H₂ reduction gas to grow cleaner and directional CNTs

   Table 1: CVD growth conditions for MWNTs
<table>
<thead>
<tr>
<th>Silicon Substrate</th>
<th>1 mm, Fe catalyst</th>
<th>30 nm, Al₂O₃ diffusion barrier</th>
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</thead>
<tbody>
<tr>
<td>Argon (Inert Diffusion gas)</td>
<td>650 sccm</td>
<td></td>
</tr>
<tr>
<td>Ethylene (Carbon source)</td>
<td>400 sccm</td>
<td></td>
</tr>
<tr>
<td>Hydrogen (Reduction gas)</td>
<td>10 sccm</td>
<td></td>
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<tr>
<td>Temperature</td>
<td>750°C</td>
<td></td>
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<tr>
<td>Growth Time</td>
<td>15 minutes</td>
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</tbody>
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   Low Temperature Plasma Functionalization:
   - Etching of the entangled top section of the CNT forests
   - Functionalization of the CNT surfaces for better suspension

2. Magnetic Assembly

   Magnetic Assembly Setup:
   - Balanced benefit of scalability and nanoparticle structure quality
   - Oscillating magnetic fields: up to 500 G, up to 5 Hz, and sine, square, and triangle waveforms
   - Real-time observation and recording: ~135 nm resolution
   - Quantitative characterization of nanoparticle distribution

   Magnetic Assembly of Superparamagnetic Nanoparticles:
   - Superparamagnetic iron oxide particles dispersed in deionized water
   - Magnetic assembly behavior parametrically studied: particle concentration, magnetic flux density, magnetic field frequency, and waveform type

   Magnetic Assembly of Ni-coated CNTs:
   - Demonstrated assembly along the magnetic fields
   - Further studies necessary

Conclusion & Future Work

- Successfully developed first generation of ferromagnetic CNTs by
  - Growing directional MWNTs using the optimized CVD process with hydrogen reduction gas
  - Functionalizing the CNT surfaces using low-temperature plasma treatment
  - Depositing thin Ni layers that form collected single magnetic domains with high anisotropy
  - Demonstrated effectiveness of magnetic assembly, control, and patterning capability by varying parameters
- Future work includes
  - Inspection of ferromagnetic CNTs: XPS for surface functionalization degree and CNT-Ni interfaces, Raman for CNT degradation, VSM for particle magnetic properties
  - Continued parametric assembly studies to deliver the capability to control and pattern nanoparticles