Magnetic composites for flywheel energy storage

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Project description

- The bearings currently used in energy storage flywheels dissipate a significant amount of energy. Magnetic bearings would reduce these losses appreciably.

- Magnetic bearings require magnetic materials on an inner annulus of the flywheel for magnetic levitation.

- This magnetic material must be able to withstand a 2% tensile deformation, yet have a reasonably high elastic modulus.

- This magnetic material must also be capable of enabling large levitation forces.

- Developing such a soft magnetic composite will enable much larger, more energy efficient storage flywheels that do not require a hub or shaft.

- Such composites are based on magnetic particles such as these:
The field exclusion problem

Particles **exclude** the magnetic field!

**Chaining** helps a bit.

- The apparent permeability of an isolated sphere is **almost unrelated** to the permeability of the material of which it is composed.
- This is why random particle composites have disappointing permeabilities.
Effective medium predictions

Series addition

\[ \mu^{-1}_{\text{eff}} = \phi \mu^{-1}_{Fe} + (1 - \phi) \mu^{-1}_{poly} \]

parallel addition

\[ \mu_{\text{eff}} = \phi \mu_{Fe} + (1 - \phi) \mu_{poly} \]

• The **series addition model** is much closer to experiment and more accurate effective medium theories.
• Creating a high permeability composite is very difficult! But is it necessary to do so?
Approach

• Combine magnetic particles of differing sizes to create a sufficiently dense solid that the field is forced to penetrate the particles.
  1. Mix the particles with a “vortex” magnetic field.
  2. Add the mixture to a polymer and degas.
  3. Centrifuge the dense mixture in a swinging bucket rotor.
  4. Remove excess polymer, restir, and recentrifuge.
  5. Cure the dense solid and characterize the magnetic and mechanical properties.
Mixed particle composites

- The best samples had loadings approaching 60 vol.%.  
- Nanopowder composites did not have high loadings because of agglomeration.
Compression tests of silicone composites

- The modulus of the magnetic composites is ~10,000 psi, which is ~60X that of the silicone polymer.
- Yield strain was 10%, but strains as high as 16% did not result in failure.
- The samples are conditioned to a higher strain after one cycle.
Magnetic permeability measurements

The inductances of the composite coils were measured as a function of drive current and frequency.

The magnetic permeability was computed from the inductance.

\[ L (\mu H) = 0.0117h \log\left( \frac{d_{out}}{d_{in}} \right) \times \mu_r \]
Our composites show ideal magnetism

- The composite inductance is completely independent of drive current (field).
- Our best carbonyl Fe composite had a volume fraction of 56 vol.% and a relative magnetic permeability of 13.0.
Our composites have a high bandwidth

- The composite permeability has a response faster than 1 μs!
- This rapid response facilitates feedback control in rapidly spinning flywheels.
The highly spherical steel shot gives a loading of 62.7 vol.%!

Our first coil demonstrated a relative permeability of 13.1.

Our first attempt at mixing these particles with 4-7 micron carbonyl Fe gave a loading of 70.0 vol.%.

These materials will be the basis of exceptional magnetic composites.
Magnetic force on a composite

**Kelvin force:** \( \mathbf{F} = -\mathbf{M} \nabla \mathbf{H} \)

- The magnetization of a body is a strong function of its shape.
- In this field geometry our composite gives a magnetic force \( \sim 84\% \) of maximum.

The flux density through the magnetic composite is essentially identical in these two cases!

The composite magnetization saturates!
Summary/Conclusions

- We have developed highly accurate methods for measuring the magnetic permeability of dense composites.

- Composite magnets made of soft silicone polymers exhibit extremely high moduli, yet can tolerate >16% compressive strains.

- Micron-size Fe particles give a relative magnetic permeability of ~13.0.

- Pure 350 micron steel shot gives loadings slightly higher that of carbonyl Fe and a comparable permeability.

- All of our composite magnets exhibit ideal magnetism and ultrafast response.

- Combining steel shot with carbonyl Fe gives significantly higher loadings (20% less void).
Future Tasks

- **Modeling the magnetic levitation circuit** to understand how the normal force depends on the composite permeability in greater detail.

- **Develop mixed particle composites** based on monodisperse steel shot to appreciably increase the packing density and composite permeability.

- Produce composites in a geometry suitable for **direct tensile testing**.

- Couple this work closely to the needs of the flywheel industry.
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