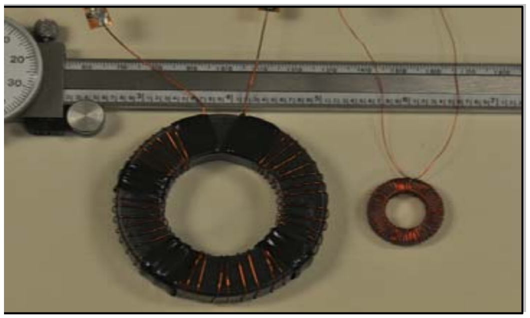

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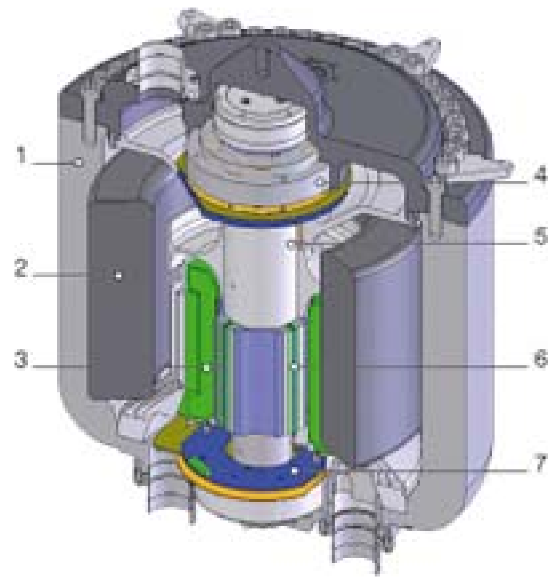
Exceptional service in the national interest

Magnetic composites for flywheel energy storage

September 27, 2012

James E. Martin



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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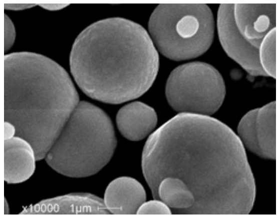
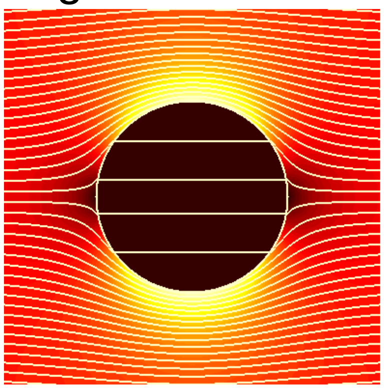
Project description

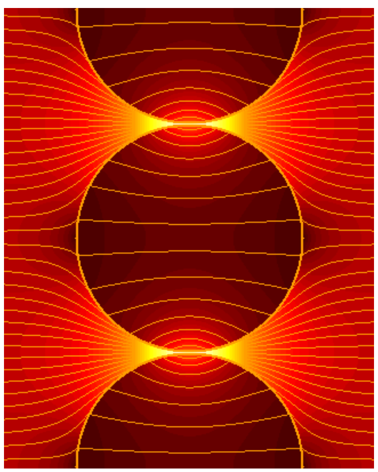
- The bearings currently used in energy storage flywheels dissipate a significant amount of energy. Magnetic bearings would reduce these losses appreciably.
- Magnetic bearings require magnetic materials on an inner annulus of the flywheel for magnetic levitation.
- This magnetic material must be able 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:



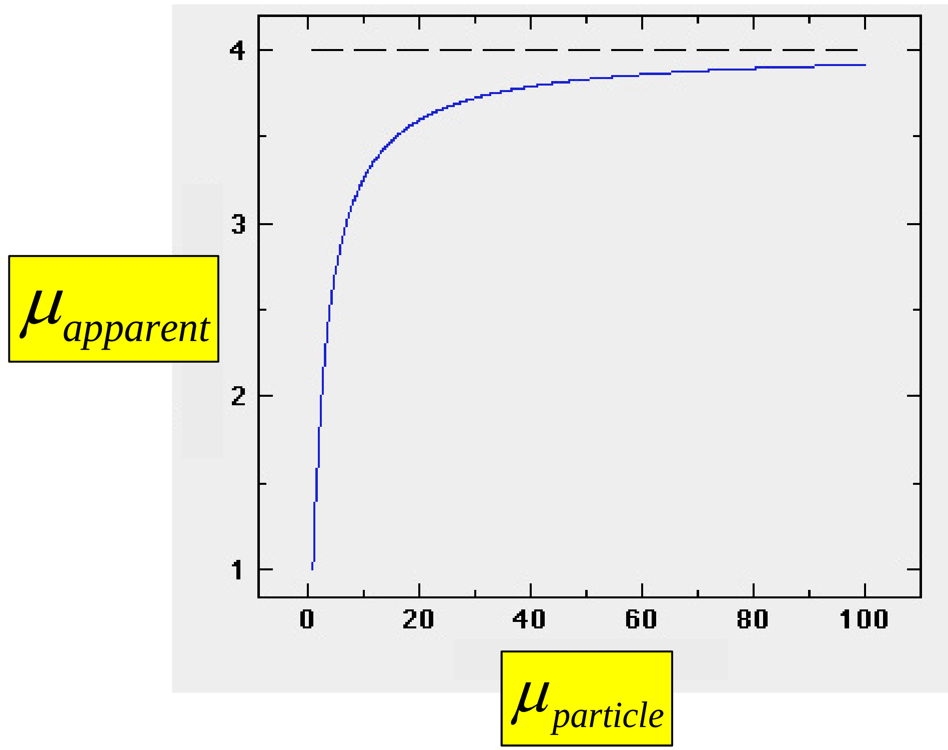
The field exclusion problem

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

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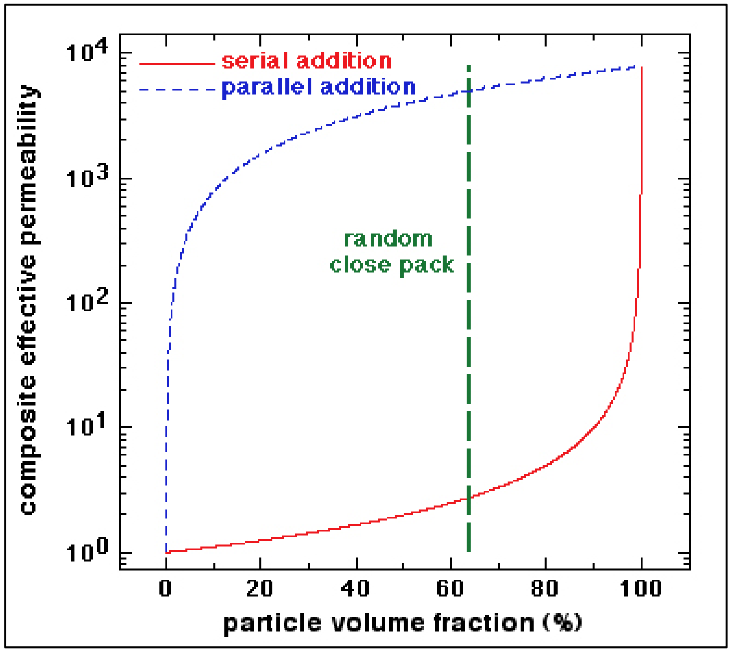
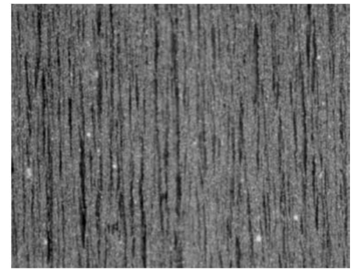
Series addition

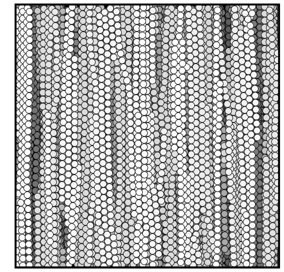
$$\mu_{eff}^{-1} = \phi\mu_{Fe}^{-1} + (1-\phi)\mu_{poly}^{-1}$$

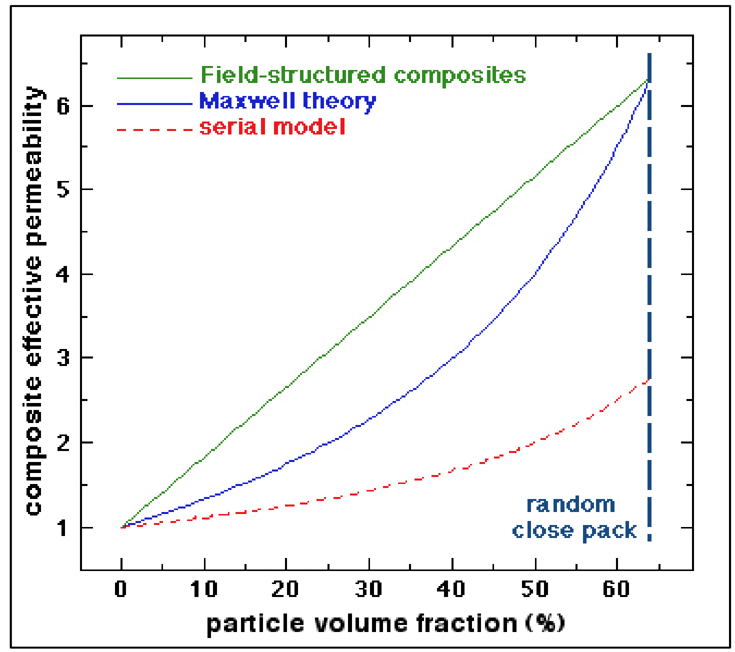
parallel addition

$$\mu_{eff} = \phi\mu_{Fe} + (1-\phi)\mu_{poly}$$







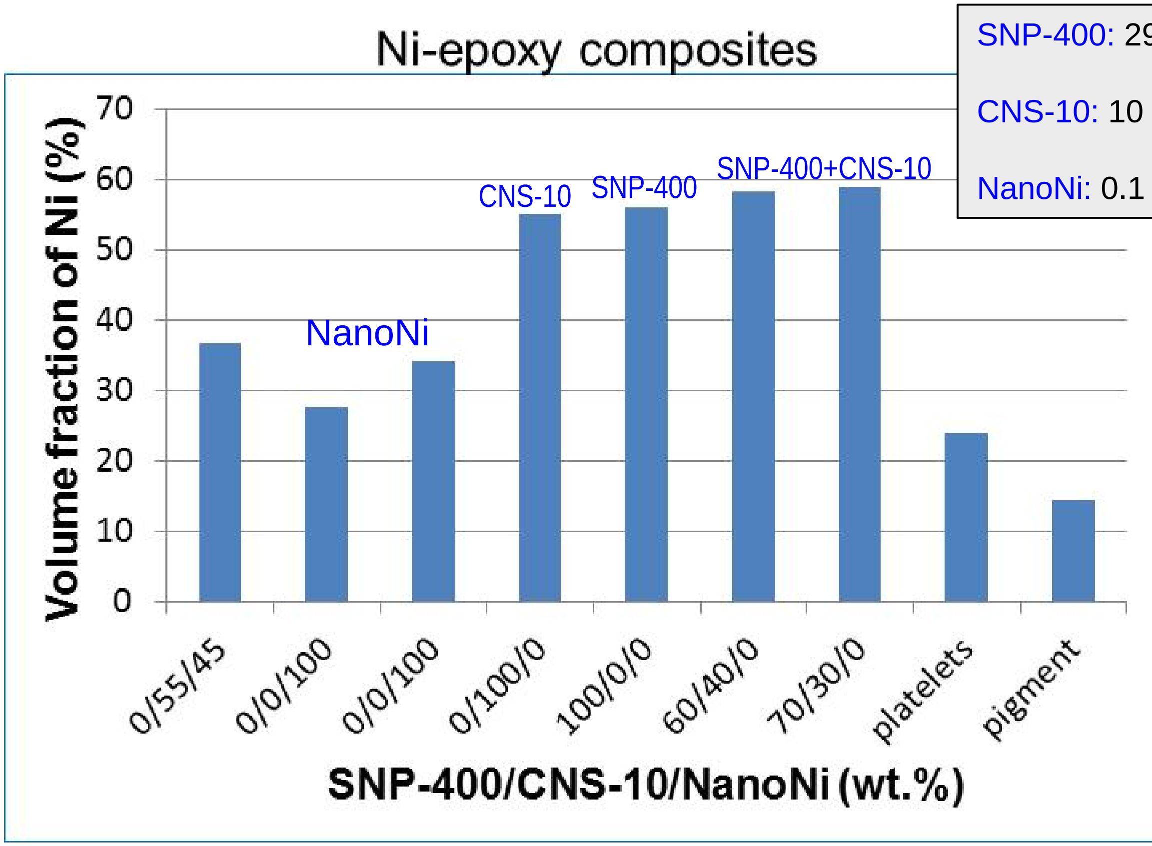


- The series addition model is much closer to experiment and more accurate effective medium theories.
- Creating a high permeability composite is very difficult! But is it necessary to do so?

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.

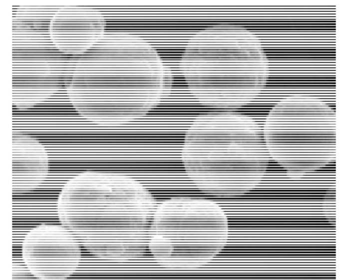
Mixed particle composites

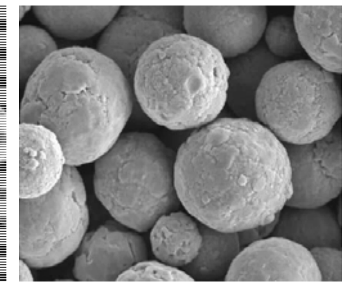


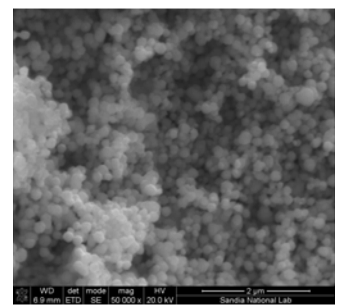
SNP-400: 29 µm spherical Ni powder

CNS-10: 10 µm conductive Ni spheres

NanoNi: 0.1 µm agglomerated nanoparticles

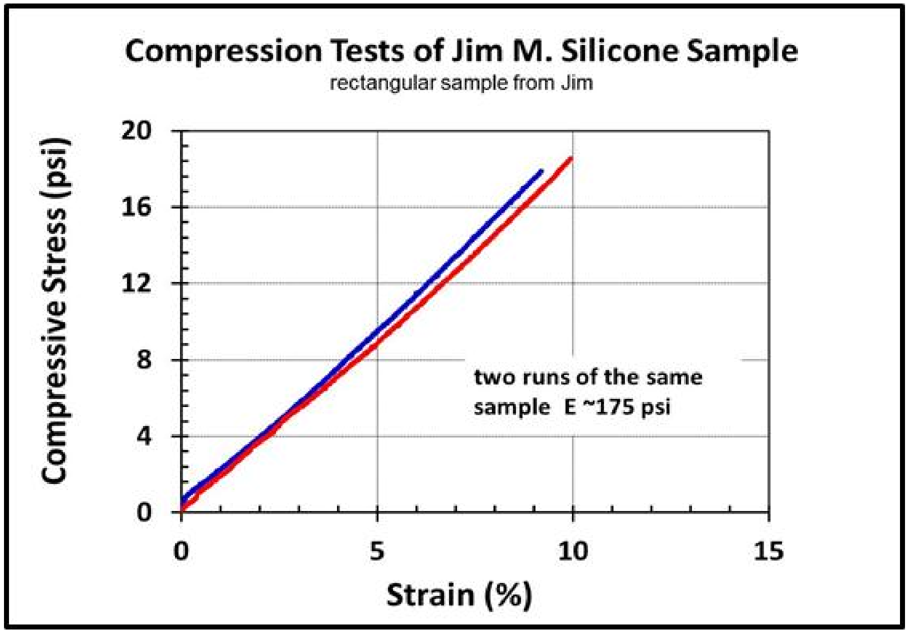

SNP-400

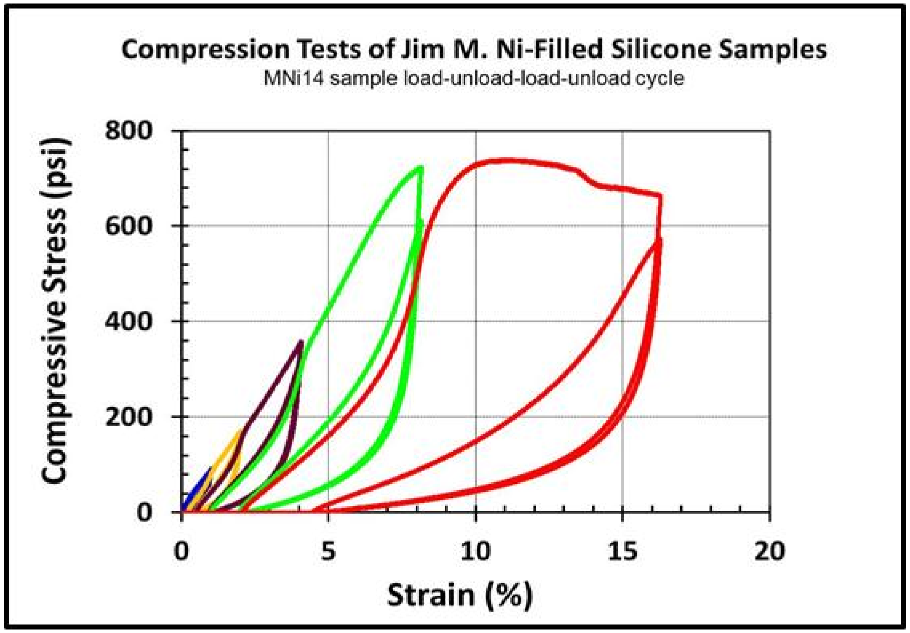

CNS-10


NanoNi

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

Compression tests of silicone composites

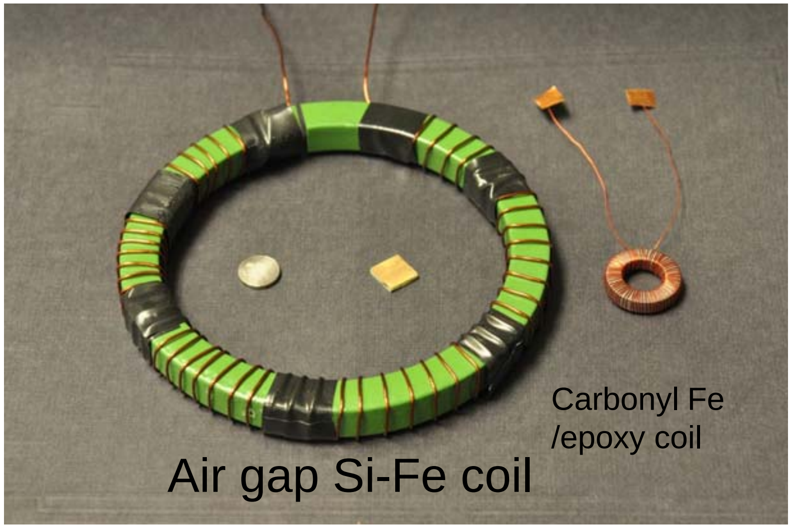


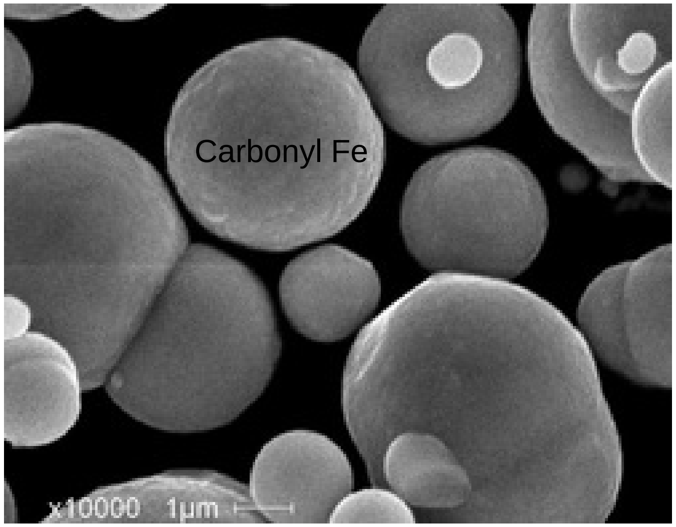


- The modulus of the magnetic composites is ~10,000 psi, which is ~60X that of the silicone polymer.
- Yield strain was 10%, but strains as high as 16% did not result in failure.
- The samples are conditioned to a higher strain after one cycle.

Magnetic permeability measurements

$$L\ (\mu H) = 0.0117 h \log(d_{out} / d_{in}) \times \mu_r$$

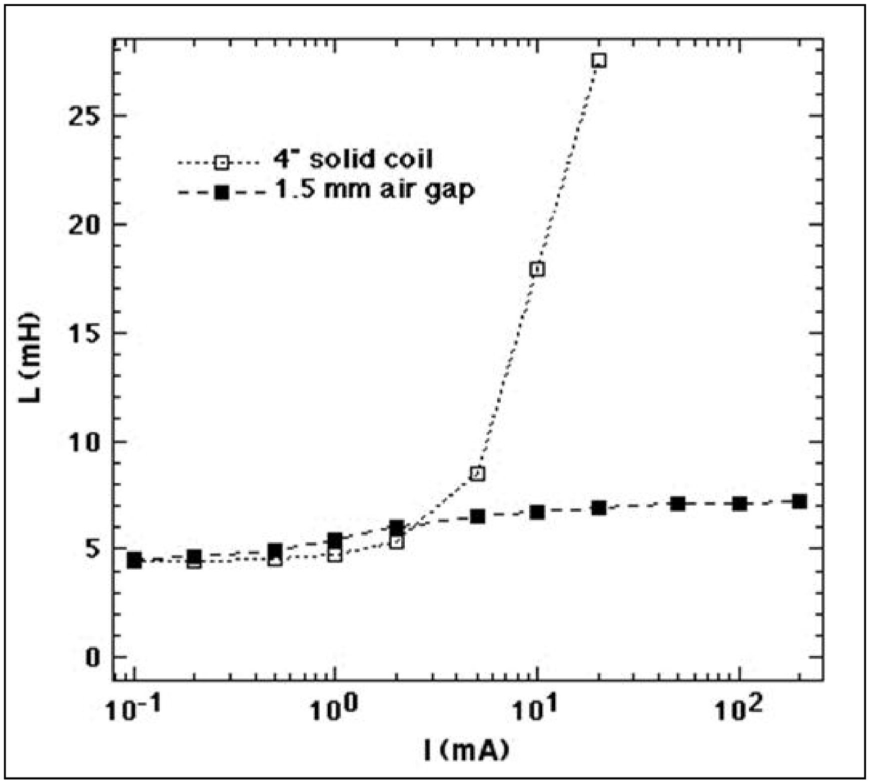




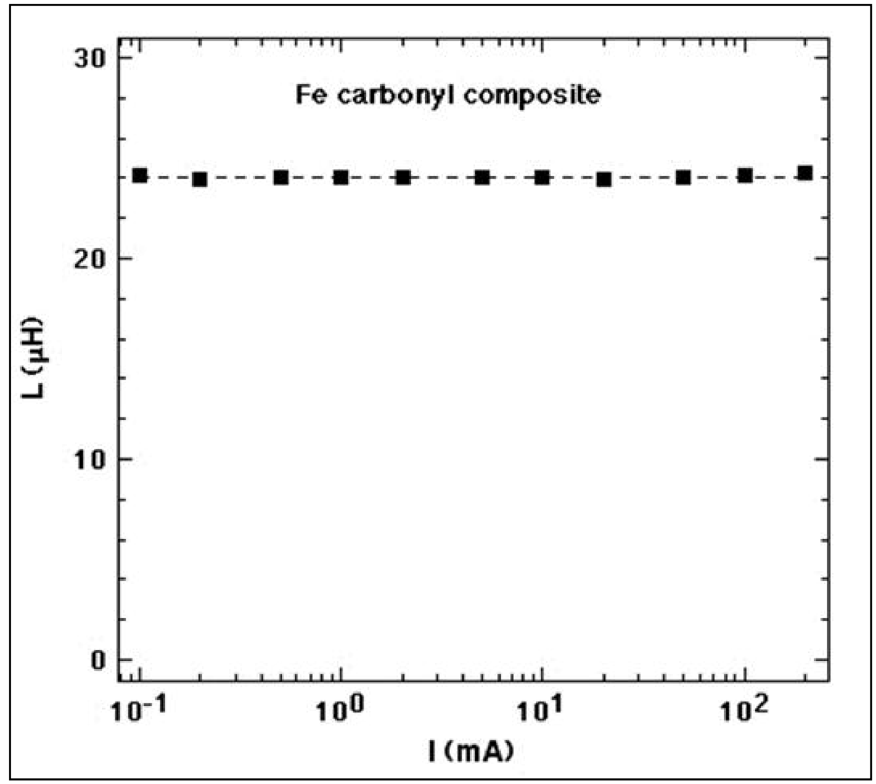
- The inductances of the composite coils were measured as a function of drive current and frequency.
- The magnetic permeability was computed from the inductance.

Our composites show ideal magnetism

Conventional Si-Fe



Our carbonyl Fe composite



- 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

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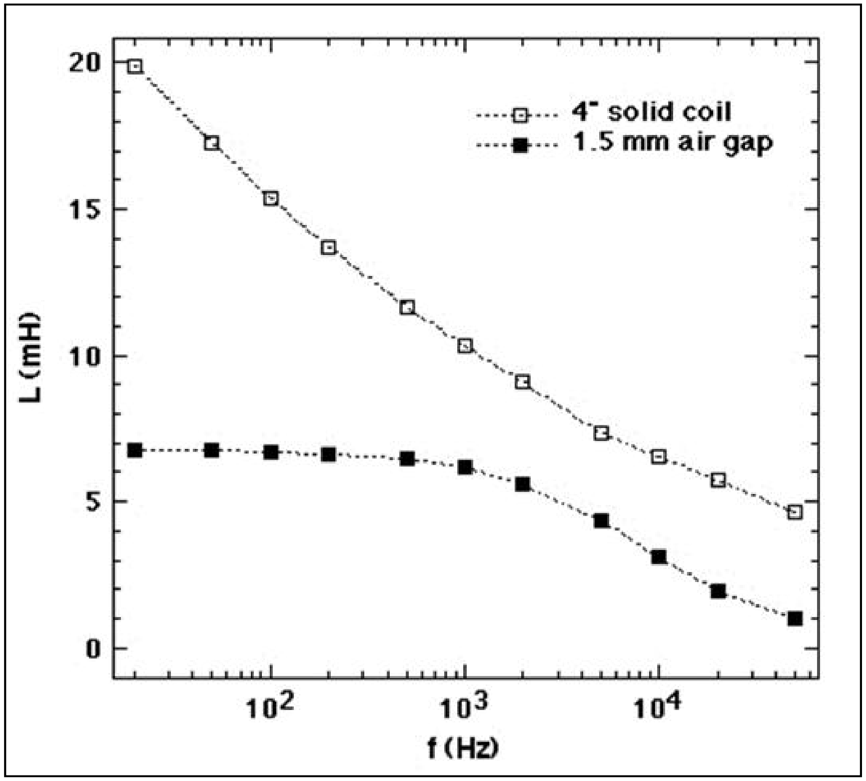
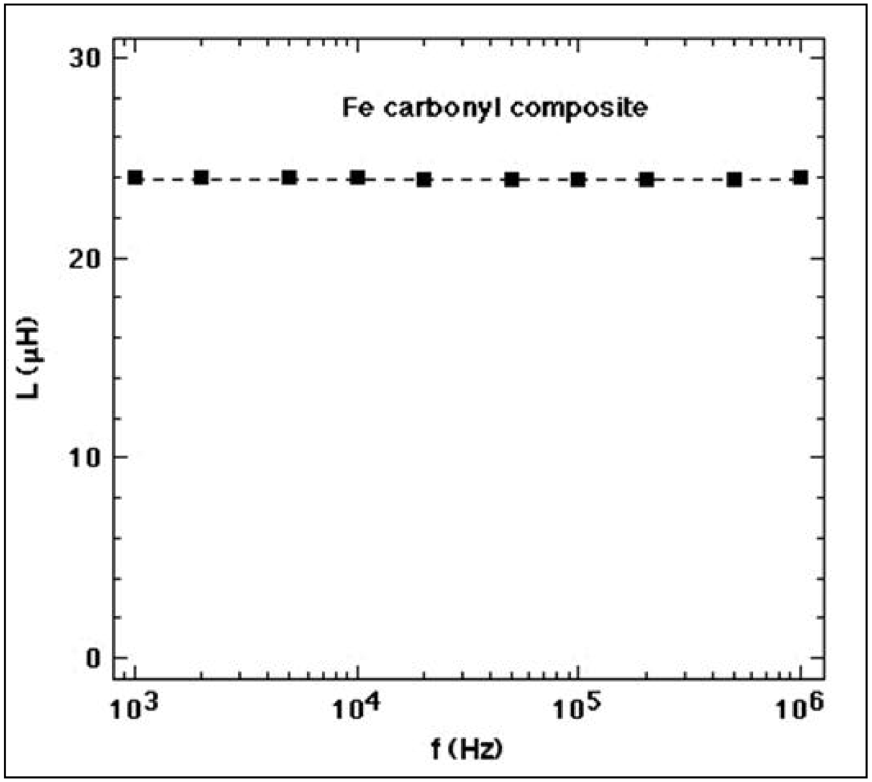
Conventional Si-Fe

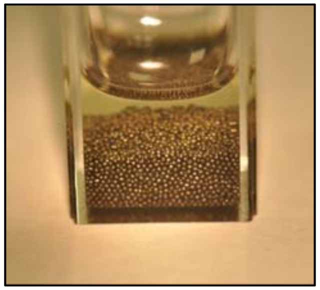


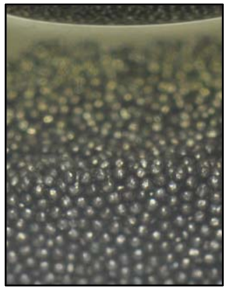
Our carbonyl Fe composite

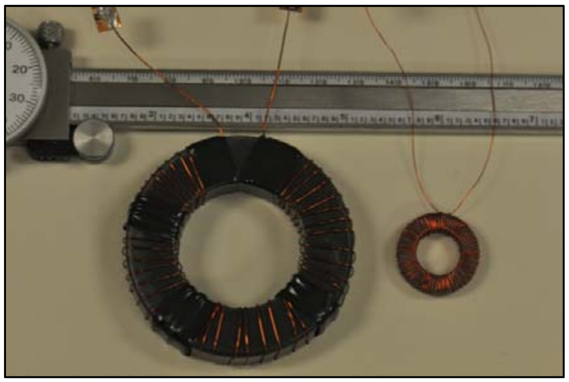


- The composite permeability has a response faster than 1 μs!
- This rapid response facilitates feedback control in rapidly spinning flywheels.

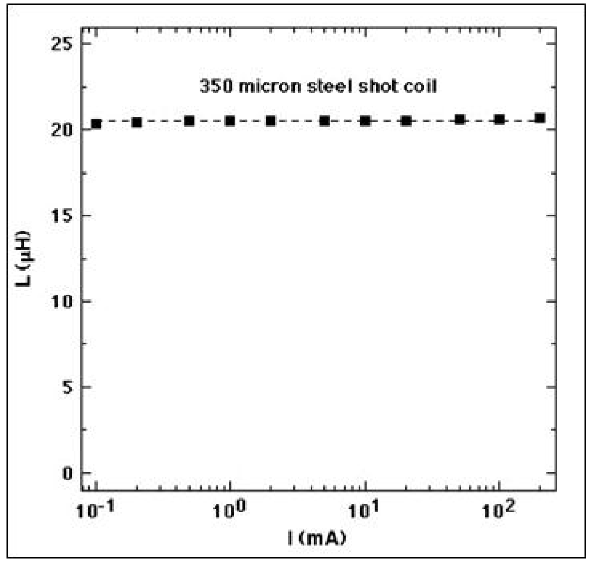
Cut-wire steel shot composites

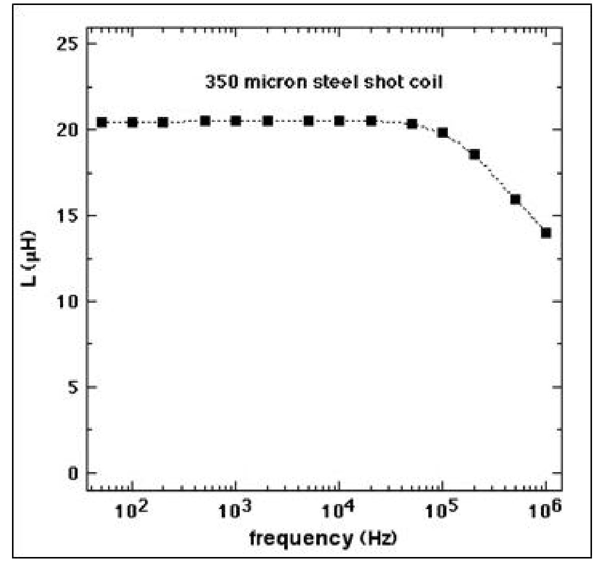






Composites exhibit linear magnetism with a fast response.



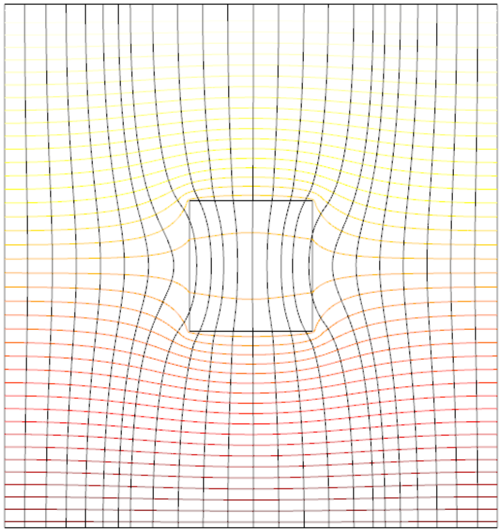


- The highly spherical steel shot gives a loading of 62.7 vol.%!
- Our first coil demonstrated a relative permeability of 13.1.
- Our first attempt at mixing these particles with 4-7 micron carbonyl Fe gave a loading of 70.0 vol.%.
- These materials will be the basis of exceptional magnetic composites.

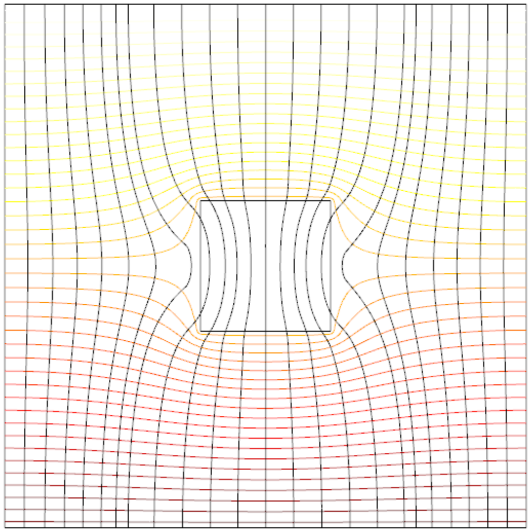
Magnetic force on a composite

Kelvin force: $\mathbf{F} = -\mathbf{M}\nabla\mathbf{H}$

permeability = 10

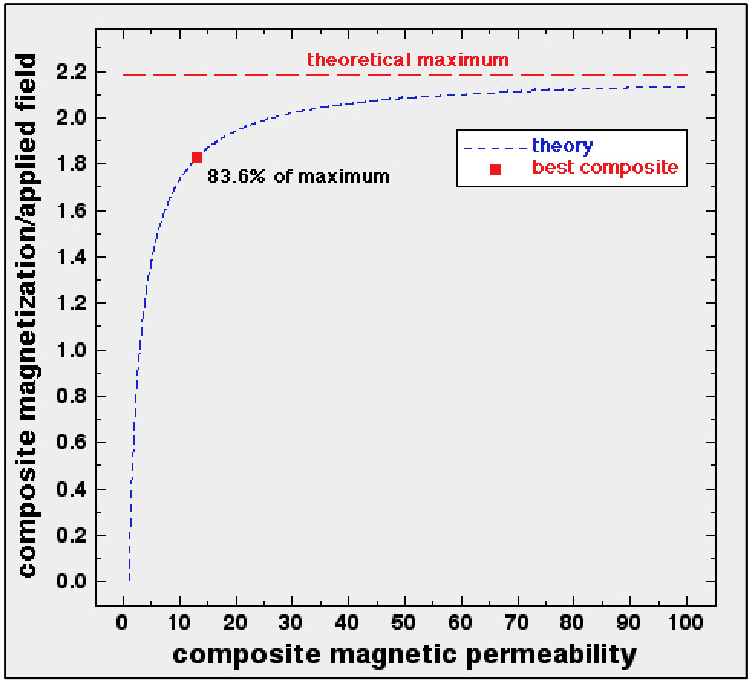


permeability = 100



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

The composite magnetization saturates!



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

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.

Contact Information

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