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Elastic magnetic composites for energy storage flywheels

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Abstract

The bearings used in energy storage flywheels dissipate a significant amount of energy and can fail catastrophically. Magnetic bearings would both reduce energy dissipation and increase flywheel reliability. The component of magnetic bearing that creates lift is a magnetically soft material embedded into a rebate cut into top of the inner annulus of the flywheel. Because the flywheels stretch about 1% as they spin up, this magnetic material must also stretch and be more compliant than the flywheel itself, so it does not part from the flywheel during spin up. At the same time, the material needs to be sufficiently stiff that it does not significantly deform in the rebate and must have a sufficiently large magnetic permeability and saturation magnetization to provide the required lift. It must also have high electrical resistivity to prevent heating due to eddy currents. In this paper we investigate whether adequately magnetic, mechanically stiff composites that have the tensile elasticity, high electrical resistivity, permeability and saturation magnetism required for flywheel lift magnet applications can be fabricated. We find the best composites are those comprised of bidisperse Fe particles in the resin G/Flex 650. The primary limiting factor of such materials is the fatigue resistance to tensile strain.

Key words: A. Particle-reinforcement; A. Polymer-matrix composites (PMCs) ; B. Elasticity; B. Electrical properties; B. Magnetic properties; C. Analytical modelling; C. Finite element analysis (FEA)

Introduction

Flywheels provide an important mechanism for storing energy from the electrical power grid during low-demand periods in order to moderate demand fluctuations that occur over timescales of about 15 minutes [1]. The energy stored in a flywheel is proportional to the product of its moment of inertia times the square of its angular velocity. The energy stored per unit mass can be increased by increasing the angular velocity of the flywheel. Steel flywheels are generally limited to 10,000 rpm, but fiber/resin composite flywheels (e.g. carbon fiber/epoxy) can be spun up to much greater rpms, due to the greater strength per unit weight of advanced composite materials. At such high angular velocities losses due to air drag and bearing friction become quite significant. Vacuum chambers are used to eliminate air drag and there is a current push to implement magnetic bearings in these flywheels [2] to reduce frictional losses and increase bearing reliability.

These magnetic bearings require that a magnetically soft ferromagnetic material be placed in a toroidal rebate on the inside of the rotor. This material is part of a reluctance circuit formed by the electromagnets and is engineered to create the required lift, Fig. 1. The rotors can weigh more than one ton, so each of the four lift magnets must generate more than a 500 lb force. The elastic modulus of the carbon fiber/epoxy rotor is lower than that of magnetic metals such as Permalloy™, so if these metals were placed into the rebate they would separate during spin up, causing the magnetic lift circuit to fail and the rotor to disintegrate, making energy recovery problematic. A suitable magnetic material must have a tensile elastic modulus lower than that of the rotor to allow it to remain in contact during spin up, but sufficiently large to prevent significant deformation of its cross section, since a rebate only has two sides. The rotor stretches about 1%

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4 during spin up, so the magnetic material must have a tensile strain at failure greater than
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6 this. Finally, the magnetic permeability and saturation magnetization of this material
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8 must be large enough to provide the required lift. The issue we investigate in this paper
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10 is whether a magnetic particle/epoxy composite can satisfy these multiple criteria.
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14 We developed two types of Fe particle composites: those containing only
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16 carbonyl iron particles and those also containing much larger cut wire steel shot particles.
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18 The latter composites we refer to as bi-disperse. In the following we first report on the
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20 magnetic properties, then the mechanical properties.
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23 24 **Experimental**

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26 **Composite fabrication.** Our initial goal was to produce magnetic particle composites
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28 having the highest achievable particle loading. Two types of composites were fabricated:
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30 those that contained magnetic particles of a single size (carbonyl iron or steel shot) and
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32 those that combined magnetic particles of greatly disparate sizes, which we call
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34 bidisperse composites.
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38 *Carbonyl iron or steel composites.* The particles used for these composites were
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40 4-7 μm carbonyl iron (obtained from Sigma-Aldrich), shown in [Fig. 2 \(top\)](#) or 300 μm
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42 cut wire steel shot (obtained from Premier Shot Company) shown in [Fig. 2 \(bottom\)](#). The
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44 composites were prepared by mixing the particles into the resin of choice. At higher
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46 loadings (>50 vol.%) the resulting pastes have a Bingham plastic rheology, something
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48 like stiff clay, and were pressed into the desired form – either a cylinder for mechanical
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50 testing or a toroid for magnetic permeability measurements – in a room temperature
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52 hydraulic press at 5,000 psi until the polymer gelled, followed by curing at 55°C
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54 overnight. A variety of resins were used: Epon™ 828 obtained from Polysciences, Inc.
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with a T403 Jeffamine™ curing agent obtained from Huntsman Corporation; a Sandia formulated rubber-modified epoxy, Hypox™ RF1341 (epoxy/carbonyl-terminated polybutadiene-acetonitrile obtained from Emerald Performance Materials) with Jeffamine™ D230 (polyetheramine obtained from Huntsman Corporation) curing agent; and a highly flexible commercial resin, G/Flex 650, obtained from West System Inc. The highest loading we achieved with the carbonyl iron particles was 56 vol.%, the steel shot enabled higher loadings, as high as 62.7 vol.%, probably due to the more spherical particle geometry reducing the fluid viscosity.

Bidisperse iron particle composites. Bidisperse magnetic particle composites were fabricated to increase the iron loading in the composites beyond that which could be attained using either the carbonyl iron particles or the steel shot alone. Our approach was to first blend 4-7 μm carbonyl iron particles into a polymer to create a dense colloidal suspension that still has a manageable rheology. A typical Epon-based paste was formed by adding 7.7 g Fe to 1.0 g of premixed resin, yielding an iron loading of 50 vol.% and a density of 4.45 g/ml. To this paste we then added the ~300 μm cut-wire steel particles. In a typical formulation we would then add 19.6 g of steel shot to obtain 56 vol.% steel shot in the carbonyl iron paste, as indicated in Fig. 3. The total iron content is then 78.0 vol.%. This approach enables the formulation of much higher loadings of Fe than can be achieved with either component alone, as great as 81.3 vol.%.

Modeling. A considerable number of different finite-element models and runs with different parameters were needed for the modeling study of the lift magnet. The finite-element program used was two-dimensional. A typical mesh element size was about

1/140 of the largest modeled feature size (not overall model size, which was much larger). Around the region of interest containing the modeled features a guard region about four times larger (in linear dimension) than this region was provided, with an increased mesh size, and a flux-impermeable boundary was applied at its outer edges. The quantity solved for at the mesh nodes (intersections between mesh triangles) is a vector potential function $\mathbf{A}$, which is set to zero at this outer boundary (Dirichlet boundary conditions). The magnetic flux density $\mathbf{B}$ is equal to the curl of the potential function $\mathbf{A}$. Over the entire solution space a typical run had on the order of 50,000 nodes. Finite-element mesh triangles can give erroneous results if the angles within the meshes are too small, and the interior angles of mesh triangles used in these solutions were limited to a minimum of 30 degrees.

Magnetic permeability measurements. Toroidal composite cores having rectangular cross-sections were wrapped with 24-30 gauge Cu wire for inductance measurements. The cores containing steel shot were pressed to final shape due to the fact that these composites do not machine well. The other composites could be easily machined. The largest cores were 2.346" O.D. and the smallest was 0.772". Sufficient wire turns were made to ensure the reactive impedance dominated the resistance over the full frequency range measured, from 20-100,000 Hz. This is possible, though not always practical, because the resistance is linear in the number of turns, whereas the inductance is quadratic. A Hewlett-Packard LCR bridge was used to make the inductance measurements. From the measured inductance, L , number of turns, N , core O.D., d_{out} , I.D. d_{in} , and height h the composite relative permeability was computed from the standard

formula $\mu_r = L(\mu H) / [0.0117h(in)N^2 \log(d_{out} / d_{in})]$.

Permeability data for samples at low volume fractions of magnetic particles (<30 vol.% Fe) were collected by a different method. These composites were machined into square bars and the magnetization of these composites was determined by using a commercial superconducting quantum interference device (SQUID) to measure the sample magnetic moment as a function of the applied field [3]. The macroscopic internal field was then determined by using a finite mesh code we wrote in FORTRAN to model the field inside the samples as a function of the external field for a range of composite magnetic permeabilities. This is the so-called demagnetizing field effect. The sample magnetization was then plotted as a function of the internal macroscopic field and from the initial slope the relative magnetic permeability was obtained. Note that in the code an extrapolation to zero composite size was made to remove the effect of image fields and a second extrapolation to zero mesh size was made to eliminate any mesh size dependence. This method agrees very well with the inductance method but is not well suited to materials with relative permeabilities greater than ~5 because the demagnetization field correction becomes too large.

A third method of magnetic permeability determination was explored but ultimately abandoned. In this method we cut a precise 1.0 mm air gap in a magnetic core comprised of an ideal magnetic material, wrapped the core with wire and measured the change in inductance when a 1.0 mm wafer-shaped composite was inserted into the core. Reluctance theory was used to compute the composite permeability. The accuracy of this approach was unsatisfactory, but perhaps could have been improved by FEA modeling the magnetic field in the core/sample. The motivation for trying this approach was the

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4 relatively simple sample fabrication required.
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9 **Mechanical testing.** Cylindrical composite samples (~1.1 inch diameter, ~2 inch high)
10 were fabricated for tensile failure tests. The center of the samples was necked down and
11 an aluminum bar was glued to each end of the machined sample. Pull chains were
12 attached to the bars and the sample was pulled uniaxially by the chains, to ensure that the
13 load is pure tension. The strain was measured across the necked down part of the sample
14 and the force was recorded by the Instron™ tensile tester. Compression tests also
15 employed the Instron™ but the samples were not tested to failure.
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28 **Electrical conductivity testing.** Composites for conductivity measurements were formed
29 into solid cylinders having low aspect ratios. The ends of these cylinders were prepared
30 by machining and sanding or by sanding alone to ensure that the bulk composite was
31 exposed as a flat surface. Fresh copper sheet electrodes were applied to the surface,
32 backed with rubber sheets and flat polymeric blocks, and then clamped under pressure
33 between precision parallel platens to ensure uniform contact of the electrodes to the
34 composite surfaces. In no case did varying the clamping pressure alter the measured
35 conductivity. Two methods of electrical conductivity testing were employed. Any
36 frequency dependence was measured with an Agilent 4284A 20Hz-1MHz Precision LCR
37 meter. Samples with low resistivities could not be measured with this bridge, due to the
38 dominance of the contact resistance of the LCR bridge leads to the Cu electrodes. Four
39 point probe dc measurements were made on these composites using a Kepco BOP36-
40 12M operational power supply/amplifier as a voltage/current source. The output voltage
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and the voltage at the Cu electrodes were measured with high impedance Fluke 189 multimeters and the current through the composite was measured with a Keithly 485 picoammeter. For the most conductive samples the voltage at the Cu electrodes was only 0.025% of the output voltage from the power supply, due to the dominance of the contact resistance between the alligator clips and the Cu electrodes. In this case the composite resistance was only 0.0055Ω. For samples where measurements could be made with both techniques the agreement was quite good.

Results and Discussion

Composite permeability. When particles are added to a continuous phase, such as a polymer resin, in order to improve some physical property the results are usually disappointing. The source of this disappointment is the expectation that a simple parallel rule of mixing describes the effective properties of the composite. For the effective magnetic permeability this rule would be $\mu_{eff} = \mu_p \phi_p + \mu_{poly}(1 - \phi_p)$ where μ_p and μ_{poly} are the particle and polymer relative permeabilities and ϕ_p is the particle volume fraction. If this equation were correct, a 30 vol.% particle composite comprised of particles whose constituent Fe had a relative permeability of 1000 would have an effective relative permeability of ~300. Reality falls far short of this estimate, especially for roughly spherical particles. The problem is that when a magnetic field is applied to a particle it polarizes and this polarization creates an internal field that opposes the applied field.

The magnitude of this so-called “depolarizing field” is highly dependent on the particle shape and orientation, and analyzing these dependencies has been the focus of numerous papers. Analytical results are available for generalized ellipsoids [4] – to

include limiting shapes such as spheres, cylinders, and plates – as well as tori [5]. These shapes are special because the internal field is uniform, regardless of particle orientation, which makes solving for the internal field analytically possible. The non-uniform internal fields of more complex shapes, such as solid rectangles, can be computed by finite mesh approaches, or, for more complex shapes, path integral techniques [6]. For randomly dispersed spherical particles at reasonably low volumetric loadings it can be shown that the effective composite relative permeability is $\mu_{eff} = \mu_{poly} + 3\mu_{poly} \phi_p / (1 - \phi_p)$, provided $\mu_p \gg \mu_{poly}$ [7], given that the magnetic permeability problem is isomorphic to the dielectric permittivity problem [8]. The term in the numerator accounts for the single particle polarization and the term in the denominator accounts for the increase in the local field due to the polarization of the other particles in the composite. This high-contrast condition is easily met for Fe particles and since the relative permeability of the polymer is extremely close to unity we can simply write $\mu_{eff} \cong 1 + 3\phi_p / (1 - \phi_p)$. For our example of 30 vol.% spherical Fe particles this expression predicts $\mu_{eff} \cong 2.3$, which is a far cry from 300. Acicular particles do better than this but it is difficult to achieve high densities with such particles. And in any case it has been shown theoretically and computationally that increases in quantities such as the magnetic permeability track increases in the suspension viscosity (the properties are essentially isomorphic), which is what limits the packing density of the particles. The point is that it is pretty tough to obtain a large magnetic permeability by adding particles to a polymer. But we will see that a really high permeability is not required.

The magnetic properties of the composites were measured by measuring the inductance of toroidal cores, as described in the experimental section. This method is

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4 preferred because this geometry eliminates demagnetizing fields associated with sample
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6 shape. Such measurements are easily made, but can be difficult to interpret. To illustrate
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8 the problem we have made measurements on 4" electric steel cores with and without air
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10 gaps. Without the air gap the inductance shows a strong dependence on both drive
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12 frequency and current, Fig. 4. The measurements also demonstrate magnetic viscosity –
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14 a reduction in the measured inductance that is logarithmic in time. With a 1.5 mm air gap
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16 cut across the coil these dependencies are greatly reduced, as is the measured inductance.
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18 This occurs because the dominant reluctance in the core is the air gap itself. The coil
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20 inductance thus becomes insensitive to the magnetic properties of the electric steel.
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25 Inductance data for a particle composite show ideal magnetization behavior, Fig.
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27 5, with very little dependence of the inductance on either the drive current or frequency,
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29 which makes extracting the permeability unambiguous. This is due to the fact that the
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31 magnetization of a particle has little to do with the permeability of the material of which
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33 it is comprised, provided this permeability is significantly greater than that of the
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35 polymer. In fact, the apparent relative permeability of an isolated spherical particle in a
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37 polymer is given by $1 + 3(\mu_p - 1)/(\mu_p + 2)$. For $\mu_p \gg 1$ the apparent relative particle
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39 permeability is $4 - 9/\mu_p \approx 4$, which is insensitive to the value of μ_p . Conceptually this
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41 effect is like cutting an air gap in a coil.
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49 This ideal magnetic behavior means the composite magnetization is independent
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51 of the flywheel angular velocity and is linear in the drive current of the electromagnet,
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53 provided the composite is far from magnetic saturation. However, it comes at the price
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55 of a low relative composite permeability. Figure 6 shows the dependence of the relative
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57 composite permeability on particle loading for both the pure carbonyl iron and the
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bidisperse composites. The data can be fit to the expression $\mu_{eff} = 1 + 6.5\phi_p/(1 - \phi_p)$, so even at 80 vol.%, which is a really difficult loading to achieve, the relative permeability is only ~ 25 . As an interesting aside, we did try magnetic flakes and achieved a permeability of 15.3 from a 20.6 vol.% composite, but were unable to increase the loading beyond this level, due to the large excluded volume of flakes. The question we must now address is how the lift depends on the permeability.

Lift versus permeability. Before giving the finite element modeling of the electromagnet and the composite toroid it is instructive to discuss some basic issues pertaining to this problem. The Kelvin force on a magnetic body is $\mathbf{F} = -\mathbf{m}\nabla\mathbf{H}$ where $\mathbf{m}$ is the magnetic moment. This force is linear in the magnetization of the composite toroid, which we will assume is square in cross-section. Because the diameter of the toroid is very large ($\sim 60''$) compared to its width ($\sim 1''$) we can treat the magnetization of the toroid as a two dimensional problem. Although the lift electromagnet is in fact in close proximity to the core we will consider the magnetization of the core as a function of its permeability for the case where it is simply placed in an initially uniform magnetic field $\mathbf{H}_0$ of infinite extent. This problem has been solved by Polya [9] using conformal

mapping and the result is a demagnetization factor n of $1/n = \left[\frac{1}{2\pi\sqrt{2}} \Gamma^2\left(\frac{1}{4}\right) \right]^2 \approx 2.1884$.

(Note: this demagnetization factor was computed for the infinite contrast case, but because the internal fields are not uniform there is a weak dependence of this demagnetization factor on permeability. We will ignore this small effect.) This demagnetization factor reduces the applied field and the expression for the macroscopic

internal field is $\mathbf{H}_{\text{int}} = \mathbf{H}_0 - n\mathbf{M}$, where $\mathbf{M}$ is the average sample magnetization and $\mathbf{H}_{\text{int}}$ is the average internal magnetic field. In the linear response regime the magnetization of the toroid is related to the toroid through its material susceptibility, $\mathbf{M} = \chi\mathbf{H}_{\text{int}}$ where in S.I. units the susceptibility χ is related to the relative permeability through $\chi = \mu_r - 1$. Combining these equations gives the expression $\mathbf{H}_{\text{int}} = \mathbf{H}_0 / (1 + n\chi_{\text{app}})$ for the internal field. The apparent susceptibility of the toroid is related to the applied field by $\mathbf{M} = \chi_{\text{app}}\mathbf{H}_0$ and is thus given by

$$\chi_{\text{app}} = \frac{\mu_r - 1}{1 + n(\mu_r - 1)}.$$

In the limit of *infinite* composite relative permeability the apparent susceptibility approaches the rather low value of $n^{-1} = 2.1884$. For a relative permeability of 25 the apparent susceptibility is 2.01, less than 10% smaller. We conclude that there might not be much value in obtaining a high composite permeability. The following results of the FEA modeling reflect these basic considerations.

FEA modeling of the lift magnet and solenoid was performed to optimize the electromagnet so as to maximize lift at constant wall power, given the geometric constraints of the 0.25" gaps and the material cross-section, and to determine if particle composites providing the required lift force could be realized. [Figure 1](#) shows a cross-section of the final iron ring lift magnet. There are 200 turns of Cu wire at 20 A per turn. There is sufficient room to increase the number of turns substantially. The flux density, $B=1.5$ T, within the Fe stator is lower than the saturation magnetism of transformer Fe ($B=2.2$ T), and within the Fe composite is only 0.4 T. The saturation magnetism of the composite should be equal to the Fe volume fraction times the saturation magnetism of

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4 Fe, so the absolute minimum Fe loading that satisfies this constraint is $0.4/2.2=18\%$.
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7 Clearly higher Fe loadings would be preferable so that the composite magnetizes to this
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9 level while still being in a linear response regime.
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11 FEA modeling of the optimized lift magnet was used to quantify how the lift force
12 depends on the permeability of the Fe composite solenoid. The data in Fig. 7 shows that
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14 for a 60" I.D. rotor and a single stator subtending 82° of arc a lift force of 1,000 lbf can
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16 be achieved with a relative magnetic permeability of only 19. This value can be achieved
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18 with an iron particle loading of 73.5 vol.%. Further increases in the permeability give
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20 diminishing returns. A composite with a permeability of 19 should have a saturation
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22 magnetism of $\sim 16,500$ G, so saturation is not a problem at these lift forces [see Fig. 7].
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28 Because we know the dependence of the lift force on permeability and the
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30 dependence of the permeability on iron loading we can plot the lift force as a function of
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32 iron loading. The plot in Fig. 6 shows a nearly linear dependence of the lift force on iron
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34 loading, which is surprising, but good news. This implies that the loading can be reduced
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36 somewhat to improve the composite mechanical properties without affecting the lift force
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38 dramatically. Lower loadings also make blending the particles into the resin much easier.
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40 Note that the lift force has a limiting value of 1305 lbf, and this actually occurs at infinite
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42 permeability. Recall that at a relative permeability of only 19 the lift force is 1000 lbf,
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44 which is 77% of this maximum.
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53 **Mechanical properties.** The mechanical properties of these materials are highly
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55 dependent on the type of loading. These materials are strong under compression, but
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57 very weak under tension. During spin up the compressive modulus of these materials
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4 greatly exceeds that which is required, 100,000 psi, exceeding the 1% strain elongation
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6 requirement proves to be difficult. For example, in an early attempt to formulate a
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8 suitable composite we used a silicone RTV resin (Gelest Optical Encapsulant 41™). This
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10 resin enabled very high compressive strains without failure, as shown in Fig. 8.
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12 However, at each increasing strain the stress-strain curve would exhibit hysteresis,
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14 probably due to the deformation of particles at their points of contact. Successive cycles
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16 at the same strain do not exhibit hysteresis, but the stress-strain curves would essentially
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18 cycle on the initial return curve at that strain amplitude, as evidenced in the displayed
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20 data. The compressive modulus, computed from the maximum stress obtained for 1%
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22 strain, is 125,000 psi, which is ~700x that of the fully cured silicone. Yielding occurred
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24 at 3.4% strain, but strains as high as 7% did not result in failure.
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31 Unfortunately, tensile tests on this composite showed failure at 0.1% strain,
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33 indicating the need for an improved resin. Epoxies have good adhesion to metals, so
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35 these were tried next. Tensile tests on a 50 vol.% carbonyl iron composite formulated in
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37 the highly elastic, rubber-modified epoxy HyPox™ RF1341 cured with Jeffamine™
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39 D230 gave a tensile failure strain of 1.45% – and a failure stress of 4,500 psi – which
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41 exceeds the 1% requirement, but not by enough to ensure fatigue resistance. The
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43 essentially linear stress-strain curves do not show yielding, only brittle fracture.
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45 However, the observed tensile modulus was 340,000 psi, which is 3x our stipulated
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53 Composites were next fabricated with the commercial epoxy resin G/Flex 650.
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55 This polymer was formulated to be glassy, but highly elastic, and its target application is
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57 gel coats on sailboats. It has a broad, indistinct glassy transition temperature and can
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sustain tensile strains of 32% in its fully-cured, neat form. It has proven to be resistant to crazing, even in such problematic, high-strain areas as sailboat rudders. Tensile tests on a 50 vol.% iron carbonyl composite showed failure at 1.75% strain, which was sufficiently large to encourage tensile testing and significantly higher than the rubber-toughened epoxy. A 45 vol.% composite was fatigue tested with strain cycles from 0.25%-1.0%. The maximum stress sustained was 5551 psi and this maximum stress changed very little during testing. However, the *minimum* stress linearly decayed from 680 psi to zero. The sample fractured after only 17 cycles. The particles generate extremely high strains and stresses near their points of contact, increasingly so as the line of centers between vicinal particles becomes parallel to the applied tensile strain. These contact points undoubtedly initiate fracture.

G/Flex 650-based composites having lower particle loadings were fabricated in order to improve the tensile failure strain and fatigue resistance of the composites. The failure strain of three composites, at 45, 40 and 30 vol.% were determined to be 1.8%, 1.95% and 3.4%, respectively, as shown in Fig. 9. Three 30 vol.% samples were fabricated for tensile strain fatigue tests from 0.25-1.0% strain. Each of these samples achieved a maximum stress of 3,800 psi at 1 % strain, indicating a tensile modulus of 380,000 psi. The best sample, cured at the lowest temperature (55 °C) finally fractured after 2,422 strain cycles, which is a considerable improvement over 17 cycles. At this loading the lift would be 450 lbf per coil, which is less than the target value of 1000 lbf. Increased lift at fixed wall power could be achieved by increasing the number of windings in the lift magnet. But at 30 vol.% Fe the saturation magnetization is 0.66 T, which is acceptable.

Electrical conductivity. Conductive materials can produce significant eddy currents when exposed to a changing magnetic flux, or when moved transverse to magnetic flux lines. These eddy currents are great for magnetic brakes, but are undesirable for flywheel applications, due to the significant loss of stored energy over time. The power dissipated by eddy currents is proportional to the material electrical conductivity, so a series of composites was fabricated for electrical conductivity to determine how their conductivities compare to pure iron ($1.0 \times 10^5 \text{ S-cm}^{-1}$ @20°C) and 3.3% Si electric steel ($2.1 \times 10^4 \text{ S-cm}^{-1}$ @20°C), a standard material for laminated transformer cores. The electrical conductivity of particle composites can be strongly dependent on applied strains [11-14], which has spurred interest into these materials as strain sensors, but we applied only a very modest compression to these samples, and insured that this was not sufficient to increase their electrical conductivity.

The electrical conductivity was measured for polymer composites made of carbonyl Fe, cut wire steel shot and mixtures thereof. Results for the various composites are in **Table I**, along with the value for electric steel containing 3.3% Si. Composites containing only carbonyl iron have conductivities ranging from $1.75 \times 10^{-12} \text{ S-cm}^{-1}$ at 33.8 vol.% Fe to $1.2 \times 10^{-2} \text{ S-cm}^{-1}$ at 56.9 vol.%, a value still more than six orders of magnitude lower than electric steel. The steel shot composite made at the maximum loading of 62.7 vol.% Fe had a conductivity of $1.7 \times 10^{-2} \text{ S-cm}^{-1}$, comparable to the most highly loaded carbonyl iron composite. At the extremely high loadings of the bidisperse composites the conductivity increases rapidly with volume fraction, rising from 5.6×10^{-3} at 75.2 vol.% to 1.9×10^1 at 80.6 vol.%, the latter value still three orders of magnitude lower than electric

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4 steel. So these composite materials can be expected to dissipate very little power,
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6 especially at loadings up to 75 vol.%, the upper limit for reasonable processability.
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10 Purely as a matter of interest we should report for that composites containing low
11 Fe loadings exhibited complex, nonohmic conductivities. For example, the ac and dc
12 conductivities for the 43.7 vol.% composite, shown in [Fig. 10](#), show a strong dependence
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14 on both frequency and applied voltage. At these loadings the transport is dominated
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16 by the polymer phase and it is likely that ionic transport is causing double layer
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18 formation, decreasing the apparent conductivity as the frequency decreases. The
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20 conductivity also increases with the applied voltage, but is always many, many orders of
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22 magnitude lower than electric steel and is not of any real concern.
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29 The conductivity of polymer composites made of hard conducting particles is
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31 quite complex. For randomly dispersed hard spheres the percolation threshold is at the
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33 dense packed volume fraction of ~65 vol.% and one might expect an abrupt transition at
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35 this loading, but reality is quite a bit more involved. Extensive work developing field-
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37 structured chemiresistors shows that the contact pressure between particles is a critical
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39 factor. Field-structured chemiresistors are simply magnetic particle/polymer composites
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41 in which Au-plated particles are chained between the electrodes using magnetic fields as
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43 the polymer resin cures. In essence, the magnetic field forces the particles to percolate in
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45 one direction, regardless of the particle loading. The conductivity of these devices is
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47 reduced significantly (up to 12 orders of magnitude) when exposed to volatile organic
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49 vapors that swell the polymer, reducing the particle contact pressure. The effect is
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51 reversible. An interesting experiment we performed illustrates the importance of particle
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53 contact pressure. We cured one field-structured composite up to the gel point in the
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4 presence of a structuring magnetic field while monitoring the electrical conductivity,
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6 which remained very low. We then turned off the magnetic field and continued to
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8 monitor the conductivity, the particles now immobilized by the gel. The conductivity
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10 increased *eight orders of magnitude* as the polymer approached full cure! The point is
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12 that the conductivity of a polymer composite is strongly dependent on the evolution of
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14 cure stresses, and is not at all a simple function of the particle loading. Epoxies shrink
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16 about 2% during cure and resins that exhibit less cure shrinkage and that have a lower
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18 elastic modulus should exhibit less conductivity. Significant cure stresses only occur
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20 after the glassy transition temperature rises above the cure temperature, so resins with
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22 lower glassy transition temperatures should reduce the evolution of conductivity.
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31 **Conclusions**

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33 We have developed strongly magnetic, mechanically stiff composites that have the tensile
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35 elasticity that make them attractive for lift magnet applications. These Fe particle
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37 composites exhibit ideal magnetic behavior in that their measured permeability is
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39 independent of either drive current or frequency over the range of our measurements.
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41 This is not true for conventional magnetic materials, such as electric steel. Two types of
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43 epoxy resin composites were formulated; those containing 4-7 micron carbonyl iron
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45 particles alone or bidisperse composites that also contained 300 micron cut wire steel
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47 shot. The bidisperse composites enabled loadings as high as 81.3 vol.% Fe, yielding a
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49 relative magnetic permeability of 25, whereas the carbonyl iron composites were limited
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51 to 56 vol.% Fe, and a relative permeability of 13.0. The magnetic permeability of the
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53 composite depends very strongly on the iron content and is accurately fit to the result of a
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self-consistent local field calculation. However, FEA modeling of the lift magnet demonstrates that the lift force is roughly proportional to the iron content, due to the rough cancellation of the non-linearities induced by the *particle* demagnetization fields and the demagnetization fields of the composite solenoid produced by the solid Fe stator. At the highest loading achieved, which gave a relative permeability of 25, the lift force was computed to be 81% of that achievable with a material of infinite permeability. This gave a lift of 1058 lbf, in excess of the 1000 lbf goal. However, there is sufficient room within the lift magnet stator to increase the lift at constant winding power by a factor of 2.7. These high lift forces can only be obtained for the bidisperse particle composites, making these a favorable choice for lift magnet applications.

These particle composites were found to be strong under compression and weak under tension, exhibiting brittle fracture at strains far below those that can be sustained by the unfilled, fully-cured resins. The elastic modulus of all composites tested greatly exceeded the 100,000 psi goal, but at loadings approaching 60 vol.% Fe the tensile failure strain dropped below the minimum requirement of 1%. 50 vol.% composites formulated with G/Flex 650 exhibited a failure strain of 1.75%, this value increasing to almost 2% at 40 vol.% and 3.4% at 30 vol.%. Fatigue testing of the 30 vol.% composite over repetitive 2 second cycles from 0.25-1.0% tensile strain produced fracture after 2422 cycles. Improvement of the fatigue properties is the next logical step in the further development of these materials for flywheel applications. One possible route is to modify the adhesion of the resin to the particle surfaces, as fracture likely initiates at the particle contacts. Another approach is to precoat the particles with a thick, soft, polymer layer that mitigates the stress singularities that would otherwise occur at the contacts between the

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4 hard Fe cores.
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Figure Captions

Figure 1. The lift magnet, showing a cross-section of the left side of the cylindrical assembly alone. The lift magnet consists of a hollow steel stator filled with Cu wire windings and a composite toroid that resides in a rebate on the upper inside of the carbon fiber flywheel. The magnet generates an inward radial force whose net value is zero due to the cylindrical symmetry and a vertical force.

Figure 2. (top) Carbonyl iron particles that are *nominally* 4-7 micron in diameter are seen to be broadly disperse, with some particles about 1 micron in size. The size distributions of these powders is somewhat broad, as reported in the literature [10]. (bottom) The 300 micron cut wire steel shot have very narrow dispersity and are reasonably spherical.

Figure 3. Volume fraction of iron in the final composite as a function of the volume fraction of the steel shot component when added to a polymeric resin already containing the indicated loadings of carbonyl iron particles.

Figure 4. The inductances of a 4" O.D. coil comprised of a solid core of wound tape electric steel and an identical coil with 1.5 mm air gap are compared. (top) The solid coil shows a strong dependence of the inductance on the drive current whereas the air gap coil does not (measurements at 20 Hz). (bottom) The solid coil inductance also shows a strong frequency dependence, whereas the air gap coil does not (measurements at 10 mA drive current). The air gap coil behaves more ideally because the gap is the dominant reluctance.

Figure 5. Inductance data for a 79.2 vol.% iron composite coil comprised of a mixture of carbonyl iron/steel shot particles formulated with Epon™ 828 and T403 Jeffamine™ curing agent. The drive-current study was performed at a frequency of 1 kHz and the frequency dependence was measured at a drive current of 25 mA, not that it matters. The weak dependence of the inductance on either variable makes composites ideal materials for lift magnets.

Figure 6. (blue) The relative magnetic permeability of the composite formulated with

Epon™ 828 and T403 Jeffamine™ curing agent increases rapidly with increasing iron content. At the maximum loading we are able to achieve a relative permeability is 25. This is far below that of pure iron, but is more than sufficient to provide the required lift. (red) The lift force is shown to be a nearly linear function of the iron loading, which maximizes at 1305 lbf, which occurs at infinite permeability.

Figure 7. (solid line) The lift force developed by a single lift magnet subtending an arc of 82° over a 60" rotor I.D. is shown as a function of the composite relative magnetic permeability. A lift force of 1000 lbf is developed at a relative magnetic permeability of 19. This value can be achieved in a composite with a 75 vol.% loading of Fe particles. (dashed line) The total flux density within the composite is given as a function of its relative permeability. These values are far below the saturation flux density of the composite. For example, for a relative permeability of 19 the saturation flux density is $\sim 1.65 \text{ T} = 16,500 \text{ G}$, which is $\sim 4\times$ the computed flux density within the composite.

Figure 8. When compressive strain cycles of increasing amplitude are applied to an 81.3 vol.% bidisperse Fe composite in a soft silicone elastomer (Gelest Optical encapsulant 41), permanent softening occurs, particularly at high strains. This softening is probably due to the deformation of particles at their points of contact.

Figure. 9. Composites formulated with G/Flex 650 epoxy at three different Fe particle loadings were tested to failure under a tensile load. The lowest loading gave a failure strain of 3.4%, which greatly exceeds the maximum anticipated strain of 1%.

Figure 10. Electrical conductivity data for a 43.7 vol.% carbonyl iron composite formulated in Epon™ 828 and T403 Jeffamine™ curing agent shows strongly nonohmic conductivity. (top) The composite electrical conductivity depends strongly on frequency and throughout the measured range can be characterized as a power law. (bottom) The dc conductivity depends on the applied voltage. Note that these are very low conductivities in any case, and would not produce any measureable eddy current heating.

Table I. Electrical conductivities of various composites at ambient temperature. (These composites were formulated with Epon™ 828 and T403 Jeffamine™ curing agent.)

ϕ_{Fe}	$\phi_{\text{carbonly Fe}}$	$\phi_{\text{steel shot}}$	ρ ($\Omega\text{-cm}$)	σ (S-cm^{-1})
33.8%	33.8%	0	5.7×10^{11}	1.75×10^{-12}
43.7%	43.7%	0	$>1.0 \times 10^8$	$<1.0 \times 10^{-8}$
48.0%	48.0%	0	9.0×10^6	1.1×10^{-7}
53.1%	53.1%	0	4.2×10^4	2.4×10^{-5}
53.4%	53.4%	0	7.6×10^4	1.3×10^{-5}
55.5%	55.5%	0	1.9×10^5	5.3×10^{-6}
56.9%	56.9%	0	8.1×10^1	1.2×10^{-2}
62.7%	0	62.7	6.0×10^1	1.7×10^{-2}
75.2%	21.8%	53.4	1.78×10^2	5.6×10^{-3}
78.9%	22.3%	56.6%	2.3×10^{-1}	4.3
80.6%	22.7%	57.9%	5.4×10^{-2}	1.9×10^1
Electric steel	—	—	4.7×10^{-5}	2.1×10^4

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