Composites Part B 97 (2016) 141–149

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Elastic magnetic composites for energy storage flywheels

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ARTICLE INFO

Article history:
Received 8 March 2016
Received in revised form
29 March 2016
Accepted 30 March 2016
Available online 5 May 2016

Keywords:
A. Particle-reinforcement
A. Polymer-matrix composites (PMCs)
B. Elasticity
B. Electrical properties
B. Magnetic properties

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.

1. 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 min [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% during spin up, so the magnetic material must have a tensile strain at failure greater than this. Finally, the magnetic permeability and saturation magnetization of this material must be large enough to provide the required lift. The issue we investigate in this paper is whether a magnetic particle/epoxy composite can satisfy these multiple criteria.

We developed two types of Fe particle composites: those containing only carbonyl iron particles and those also containing much larger cut wire steel shot particles. The latter composites we refer to as bi-disperse. In the following we first report on the magnetic properties, then the mechanical properties.

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http://dx.doi.org/10.1016/j.compositesb.2016.03.096
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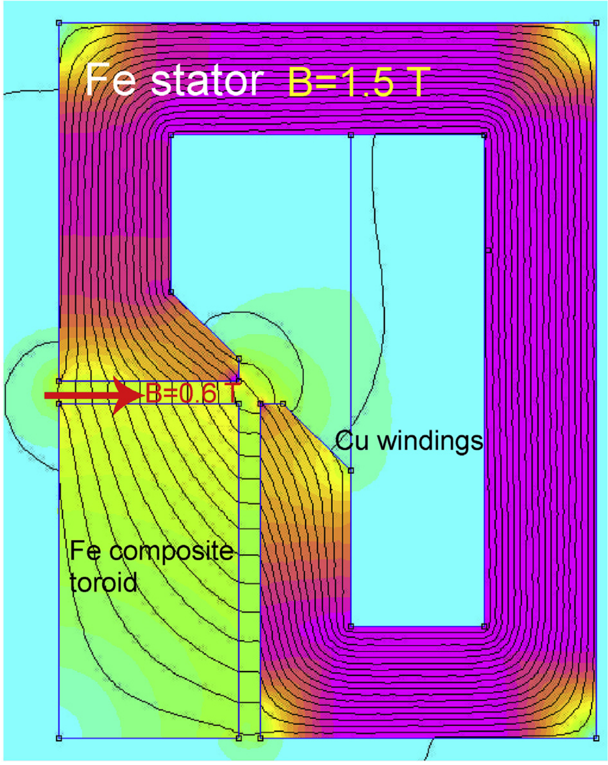

Fig. 1. The lift magnet, showing a cross-section of the left side of the cylindrical assembly alone. The lift magnet consists of a hollow steel stator filled with Cu wire windings and a composite toroid that resides in a rebate on the upper inside of the carbon fiber flywheel. The magnet generates an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

2. Experimental

2.1. *Composite fabrication*

Our initial goal was to produce magnetic particle composites having the highest achievable particle loading. Two types of composites were fabricated: those that contained magnetic particles of a single size (carbonyl iron or steel shot) and those that combined magnetic particles of greatly disparate sizes, which we call bidisperse composites.

2.1.1. *Carbonyl iron or steel composites*

The particles used for these composites were 4–7 μm carbonyl iron (obtained from Sigma–Aldrich), shown in Fig. 2 (top) or 300 μm cut wire steel shot (obtained from Premier Shot Company) shown in Fig. 2 (bottom). The composites were prepared by mixing the particles into the resin of choice. At higher loadings (>50 vol.%) the resulting pastes have a Bingham plastic rheology, something like stiff clay, and were pressed into the desired form – either a cylinder for mechanical testing or a toroid for magnetic permeability measurements – in a room temperature hydraulic press at 5000 psi until the polymer gelled, followed by curing at 55 °C overnight. A variety of resins were used: Epon™ 828 obtained from Polysciences, Inc. 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.

2.1.2. *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.%.

2.2. *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 **A**, which is set to zero at this outer boundary (Dirichlet boundary conditions). The magnetic flux density **B** is equal to the curl of the potential function **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°.

2.3. *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 to 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].