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Magnetic Laminates for Motor Slot Wedges and Other Applications

A. Krzak[1], G. Matula[1], A.J Nowak[1], C. Ebbing[3], T. Haugan[3], M. Sumption[2]

[1]Silesian University of Technology, Scientific and Didactic Laboratory of Nanotechnology and Materials Technologies, Gliwice, Poland

[2] CSMM, Materials Science Department, The Ohio State University

[3] Air Force Research Laboratories, WPAFB, Dayton, OH

Email: anna.krzak@polsl.pl

Abstract. We have examined the properties of G-10-Fe, a commercially manufactured fiber-reinforced epoxy with a 70 wt% inclusion of Fe powder, and the advantages of this material in motor slot wedges are presented. The microstructure of G-10-Fe was observed by SEM/EDS and its magnetic properties were measured in terms of magnetization, saturation magnetization and AC loss. The saturation magnetization was 150 Am^2/kg, as determined by vibrating sample magnetometry (VSM). Core losses were measured by spinning magnet calorimetry (SMC). In loss measurements made at applied field frequencies of 10 to 120 Hz essentially only hysteretic loss was present, the per cycle loss was ≅ 19 mJ/cm^3. The absence of eddy current loss made G-10-Fe more suitable than bulk Fe for use as motor slot wedge material.

1. Introduction

Soft Magnetic Composites (SMC) play a significant role in the electrical, computer and telecommunications industries. They are used for microwave communication, power distribution, electrical and mechanical energy conversion [1,2,3]. These materials are particularly interesting for electrical machine applications, especially when combined with new design principles and manufacturing techniques [1,4,5]. Many researchers have studied the processing and the effect of additives on the magnetic properties of these materials, as well as their applications [1,2,6].

It is common for SMCs to be magnetically isotropic, consisting of small, isolated iron particles in an electrically insulating matrix, as noted in an extensive literature review conducted by Shokrollahi [1]. They can be easily shaped into three-dimensional structures by powder forming. SMCs have diffuse porosity, leading to lower permeability. Sarfraz et al. [6] developed a composite material consisting of iron powder and PEEK, which had a magnetization of 185.8 Am^2/kg at 300 K. Ramajo et al. [7] examined the magnetic and dielectric properties of Fe_3O_4/epoxy resin composites and their magnetic saturation was 57.0 Am^2/kg (100 wt% Fe_30_4) and 42.3 Am^2/kg (75.5 wt% Fe_30_4) at 300 K. Zhang et al. [8] and his research team obtained iron-based soft magnetic composites by using surface treatment with phytic acid. Their magnetic saturation was 245 Am^2/kg. The material from Laxminarayana et al. [9] material consists of: nanocrystalline Fe_3O_4 particles and epoxy resins. The study included the examination of core losses using a *M-H* Loop tracer in the frequency range of 0 to 1500 Hz for both

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coated and uncoated iron powder. Core loss in 100 Hz of uncoated iron was 82 W/kg and coated iron - 19 W/kg. Gélinas et al. [10] compared the core loss of iron/epoxy materials with high curing temperatures at 60 and 400 Hz. He confirmed that at low frequency, the hysteresis loss counts for more than 90% of the total core loss in these composite materials. At 60 Hz, an iron-resin material cured at 400°C, has a core loss of 9.9 W/kg, while at 400 Hz it is 85 W/kg.

The aim of the research is to measure the magnetic characteristics of a G-10 laminate with Fe powder loading, which in the future can be applied in various temperature applications.

2. Experimental materials

The material tested in this research is a laminate with an epoxy matrix, nominally 70 wt% Fe powder, and glass-fiber reinforcement. The material was supplied by IZOERG (Gliwice, Poland). Test samples were made in a three-step process, starting with mixing the resin with a solvent loaded with iron powder, hardener and catalyst. The next stage was the impregnation of the glass fabric with the mixture and allowing solvent evaporation. Then the process was completed in a hot press. The magnetic moment of this SMC is provided by Fe.

3. Research methodology

3.1. Magnetic testing

M-H hysteresis loops were measured at 4 K, 20 K, 77 K and 300 K using a Quantum Design (California, USA) Physical Property Measurement System (PPMS) with the Vibrating Sample Magnetometer (VSM) option. The sample was cut into a rectangular prism with dimensions 5.6 mm x 4.4 mm x 3.8 mm and it had a mass of 331.8 mg. The ramp rate of the measurement was 2 mT/s, with a maximum applied magnetic field of 2 T. Analysis of the hysteresis loops were used to determine saturation magnetization "M_s" [Am^2/kg] and coercivity "H_c" [T].

The AC loss measurement (fig. 2) used here was previously described in Ref [11,12]. The system, generates a high *B* and *dB/dt*, uses an array of permanent magnets affixed to a rotor to supply a nearly sinusoidal radial field of 0.566 T, at frequencies up to 240 Hz (at 3600 RPM) to a sample mounted in a double wall calorimeter. The sample itself is at 77.2 K, immersed in liquid nitrogen. The loss is then measured by calibrated liquid nitrogen boiloff. Further details are provided in Ref [11,12]. For our measurements, the frequency range of the applied field was 10 to 120 Hz. The sample measured was 4 mm wide, 5 mm thick, and 5 cm long. The radial field was applied perpendicular to the sample length. However, the sample was expected to be isotropic.

Micrographs of the composite were captured utilizing an electron microscope housed at the Center for Electron Microscopy and Analysis (CEMAS) at The Ohio State University (OSU). The microscope was equipped with both secondary electron (SE) and backscattered electron (BSE) detectors. The investigation made use of an Energy Dispersive X-ray Spectroscopy (EDS) system, useful for elemental composition.

4. Results

Figure 1 represents the behaviour of G-10-Fe iron powder laminates (a soft ferromagnet) measured by vibrating sample magnetometer (VSM) at 4 K, 20 K, 77 K and 300 K. The maximum applied magnetic field was 2 T. Table 1 shows the saturation magnetization.

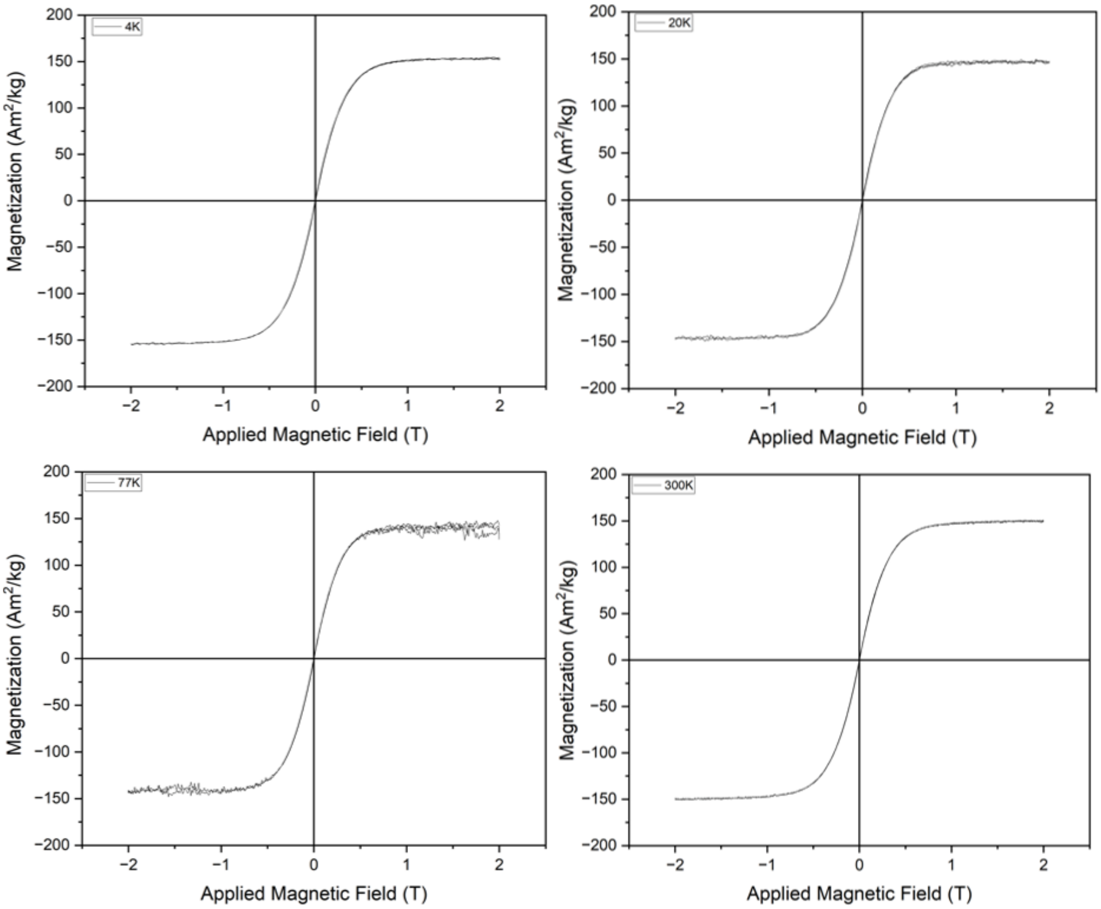

Figure 1. Magnetic hysteresis loops at 4K, 20K, 77K and 300K obtained for the magnetic epoxy glass laminate.

Table 1. Parameters of magnetic tests.

Temperature [K]	Saturation Magnetization, M_s [Am^2/kg], ±5%
4 K	153
20 K	147
77 K	143
300 K	150

The values of magnetic coercivity and residual magnetization of the material are close to zero, that is, it was a soft ferromagnet. There was no observable temperature dependence of the saturation magnetization (some slight increase with decreasing temperature should occur, but it is not resolved here). We note here that the saturation magnetization of Fe is 217.5 emu/g (1 emu/g = Am^2/kg). The density of G10 is 1.80 g/cm^3, while that of Fe is 7.87 g/cm^3. The average composite density should then be 3.91 g/cm^3. Ignoring density for a moment, if 70 wt% of the composite is Fe, then we should expect a saturation magnetization of 153 Am^2/kg. Correcting for density, we should expect 198 Am^2/kg, suggesting the actual loading may be below the nominal Fe loading. Assuming nominal mass loading of Fe at 70 wt%, the saturation magnetization should be 153 Am^2/kg, close to our measured value.

Figure 2 shows the relation between G-10-Fe material's core (power) loss and frequency at 10-120 Hz and the obtained per cycle loss ($Q = P/f$) values are summarized in Table 2.

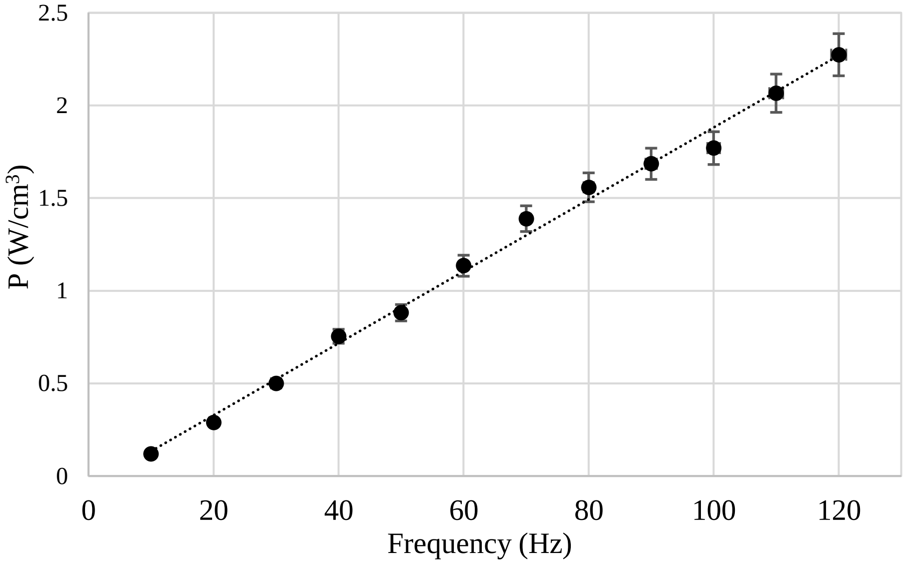

Figure 2. Core loss of magnetic epoxy glass laminate.

In general, we can expect losses to follow

$$Q_{tot} = Q_{hys} + Const * \frac{dB}{dt} \tag{1}$$

Here $Q = P/f$, and the total loss has hysteretic (ferromagnetic) losses and eddy currents (the second term of Eq (1). The constant in front of the second term is inversely proportional to the resistivity of the material, and directly proportional to the square of the width of the region of eddy current circulation and a geometric factor. Table 2 shows the core losses converted to per cycle loss, and comparing to Eq (1), we see that the ferromagnetic component of the loss (the hysteretic component) is very dominant, with negligible eddy current contributions. This result is highly desirable, as the eddy currents are suppressed because of the powder composite nature of the material, while substantial saturation magnetization remains. Per cycle losses are about 19 mJ/cm^3, and at 60 Hz, this is 180 W/kg core loss.

Table 2. Per cycle Core losses.

Frequency [Hz]	Q [mJ/cm^3]
120	19
110	19
100	18
90	19
80	19
70	20
60	19
50	18
40	19
30	17
20	14
10	12

To understand the microstructure of our G-10-Fe sample, we used an SEM coupled with EDS, and the results are given in Figure 3, below.

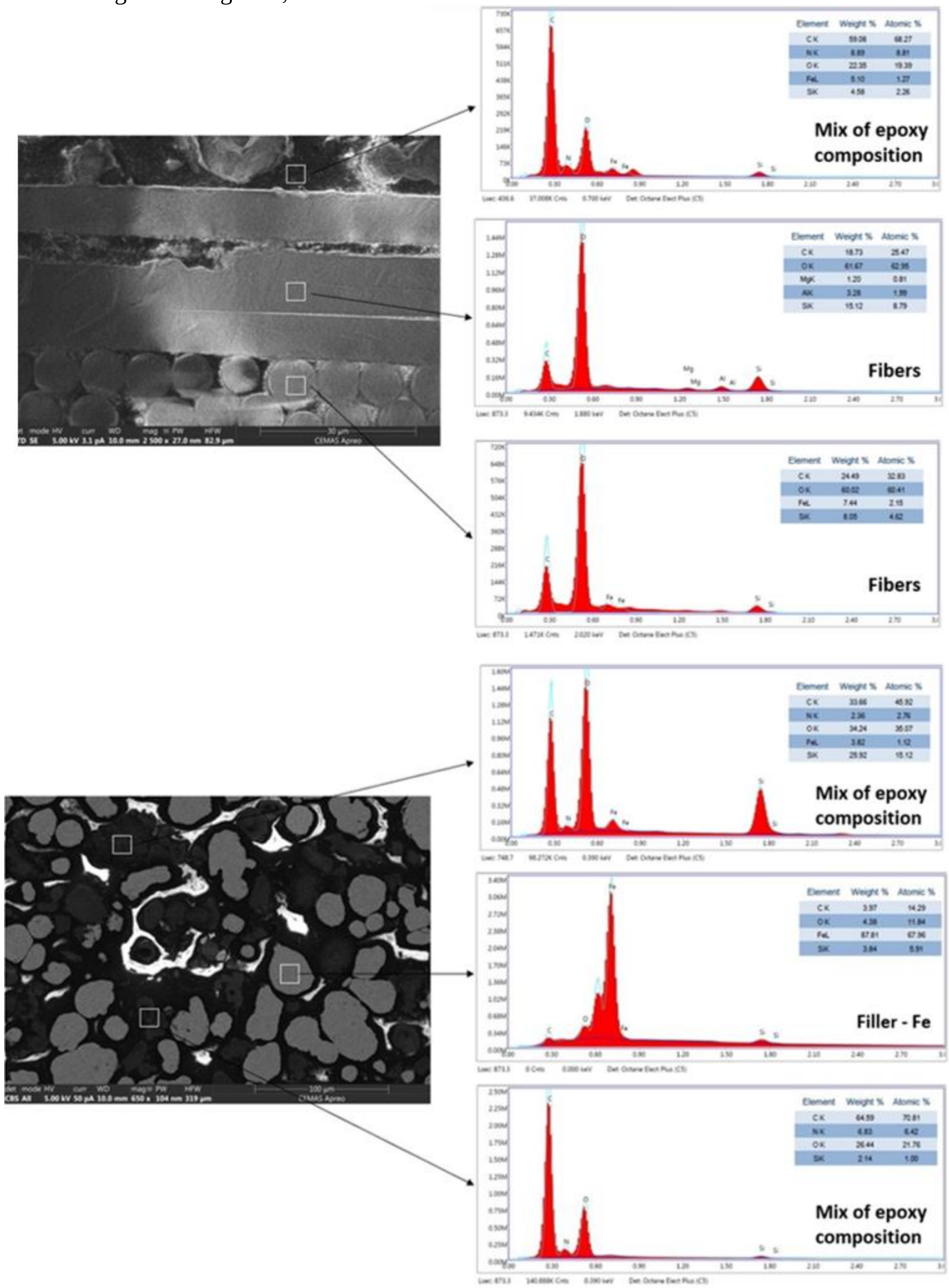

Figure 3. SEM-EDS of (top) entire G-10-Fe laminate, and (bottom) zoomed in on Fe-loaded epoxy region.

We can see circular objects roughly 10 μm OD, these are fibers. We also see horizontal layers 5-10 μm thick, these are also fibers. The dark matrix is a mixture of the epoxy resin composition with iron powder, and the irregular gray regions are filler particles - iron powders. Higher iron content increases magnetic saturation via a rule of mixtures. Smaller iron particles possess larger surface areas, coating content, and lower core loss [3].

5. Conclusion

The primary objective of this study was to develop a novel SMC to minimize energy losses in the core, reduce weight, and improve the SMC manufacturing process. We started by using SEM and EDS to characterize our prepared samples, and the expected distribution of Fe, fiber, and epoxy was observed. Next, we explored the magnetic properties of the SMCs at temperatures of 4 K, 20 K, 77 K and 298 K, using a vibrating sample magnetometer. A saturation magnetization of 150 Am^2/kg was achieved, with no observable temperature dependence. Remanent magnetization and coercive field were nearly zero. We used a Spinning Magnet Calorimeter to measure the core losses, and with an applied field of 0.566 T, the per cycle core losses were $\cong$ 19 mJ/cm^3 in the range of 20-120 Hz, with negligible eddy current contributions. Thus, our composite combines light weight, low losses, and good magnetic properties, attractive for electric motor and other applications, both at and below ambient temperatures.

The next stage of research is to compare the magnetic properties of glass-epoxy laminates filled with iron powder with newly developed composite materials in which iron powder will be replaced with magnetite powder. The testing of mechanical and magnetic properties under low temperature and cryogenic conditions is planned.

6. References

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