Letter to the Editor

Effect of electrical resistivity on core losses in soft magnetic iron powder materials

L.P. Lefebvre[a],*, S. Pelletier[a], C. Gélinas[b]

[a] Industrial Materials Institute/National Research Council Canada, 75 de Mortagne, Boucherville, Québec, Canada J4B 6Y4
[b] Quebec Metal Powders Limited, 1655 Marie-Victorin, Tracy, Québec, Canada J3R 4R4

Abstract

Iron powder should be electrically insulated with a dielectric to reduce eddy current losses in components fabricated by powder metallurgy intended for AC soft magnetic applications. However, most of the dielectrics act as distributed air gaps and reduce the apparent permeability of the material. To obtain materials with good magnetic properties, the dielectric amount should then be kept as low as possible while maintaining low eddy current losses. This paper presents the influence of electrical resistivity on core losses in iron powder compacts at low frequency ($f < 1$ kHz). The results obtained show that a resistivity one order of magnitude higher than the resistivity of iron (~ 0.1 μΩ m) is sufficient to maintain low eddy current losses in powder cores at frequencies below 100 Hz. © 1997 Elsevier Science B.V. All rights reserved.

Recent developments in powder metallurgy (P/M) and more specifically in insulated powders have made iron powder cores suitable for many AC soft magnetic applications. P/M technology is suitable for economic mass production of near net shape products having isotropic thermal, magnetic and electric properties. It is possible to optimize the magnetic properties of iron powder cores (i.e. maximize the permeability while maintaining the eddy current losses low at the operating frequency) by varying the dielectric content, its nature and distribution.

Core loss is defined as the power absorbed by a core under stated conditions of applied time-varying magnetic field [1]. Core loss is mainly composed of hysteresis loss P_h and eddy current

* Corresponding author. Tel.: + 1 514 641 5031; fax: + 1 514 641 5105; e-mail: louis-philippe.lefebvre@nrc.ca.

Table 1
Description of the samples characterized

Sample	Powder	Compaction (°C)	Heat treatment	Resistivity ($\mu\Omega$ m)
A	Iron	150	1 h at 175°C in air	0.6
B	Iron	150	None	1.2
C	Iron	65	None	4
D	Iron + 0.2 wt% resin	65	1 h at 175°C in air	22
E	Iron + 0.4 wt% resin	65	1 h at 175°C in air	44

losses P_c. Hysteresis loss varies linearly with frequency while eddy current losses vary with the square of the frequency. The hysteresis loss depends on the composition and the structure of the material and can be determined from the area of the hysteresis loop. The eddy current losses are inversely proportional to the electrical resistivity of the material and vary with the second power of the eddy current path length (lamination thickness in stack assemblies and powder particle size in powder cores). Using the Steinmetz equation, total power loss P_{tot} may be expressed as follows:

$$P_{tot} = W_{tot}f = W_h f \times W_e f = nB^{1.6}f + eB^2 f^2 \qquad (1)$$

where W is the energy dissipated, f the frequency, B the magnetization and n and e are constants. The two losses may be separated by dividing the total loss P_{tot} measured at different frequencies by the measuring frequency f, and plotting the results against frequency. At low frequency, the relation between the core loss and the measuring frequency is linear. The value extrapolated to $f = 0$ Hz corresponds to the hysteresis portion of the loss W_h and the difference between W_h and W_{tot} represents the eddy current losses W_e. The method of separation of losses has been applied for many years for the separation of losses in commercial silicon–steel transformer sheets. This method is reliable when frequency and permeability are low ($f < 100$ Hz, $\mu < 5000$) [2]. Weglinski [3] has used this technique to show that eddy current losses are low in iron–0.5 wt% epoxy composites at 50 Hz.

This paper presents the influence of resistivity on eddy current losses in iron powder cores. Samples with different resistivities have been prepared by varying the composition and the manufacturing conditions. A description of the samples is given in

Table 2
Particle size distribution of the ATOMET 1001HP

US sieve sizes	Opening (μm)	% weight
+ 60	+ 250	Trace
− 60 to + 70	212	0.1
− 70 to + 100	150	11.0
− 100 to + 140	106	20.3
− 140 to + 200	75	22.5
− 200 to + 230	63	12.0
− 230 to + 325	45	15.8
− 325	− 45	18.3

Table 1. The effect of the processing parameters and dielectric content on the resistivity of the samples has already been discussed elsewhere [4, 5]. A high-purity water-atomized iron powder developed for magnetic applications (ATOMET 1001HP supplied by QMP) was used in these experiments. The granular distribution of the powder is presented in Table 2. There was no admixed lubricant in the iron or iron-resin powders and the die walls were lubricated with a graphite spray. Rectangular bars ($3.175 \times 1.27 \times 0.635$ cm) and rings (o.d. = 5.26 cm, i.d. = 4.34 cm, $t = 0.635$ cm) were pressed at 620 MPa (45 tsi) at 65 and 150°C. The electrical resistivity was measured on five bars using a four-point contact probe (0.8 cm between contact points) and a micro-ohmmeter adapted for this application. Side and thickness effects were taken into account for the calculation of the electrical resistivity. Five readings were taken on top and bottom faces of each bar and averaged. Magnetic properties (permeability and core loss) were measured from 20 Hz to 1 kHz. The apparent permeability and core loss were evaluated for

a magnetization of 0.5 T using a ACT/SMT-500 computer-automated magnetic hysteresis graph. Rings were wound with 250 primary turns of #24 gauge copper wire and 250 secondary turns of #30 gauge copper wire.

The effect of resistivity on core loss/cycle at different frequencies is presented in Fig. 1. At low frequency, the relation between the loss per cycle and frequency is linear (Fig. 1a). As previously mentioned, the loss per cycle extrapolated to 0 Hz corresponds to the hysteresis portion of the loss. This value is similar for the 5 samples ($W_{0\ Hz}$ = 0.059 W kg^{-1} s^{-1}, S.D. = 0.003) and does not seem to be strongly affected by the processing parameters used here and by a variation in the resin content from 0 to 0.4 wt%. The hysteresis loss is not density or resistivity sensitive and is mainly

affected by the chemistry and the structure of the magnetic material. The hysteresis loss depends on the starting powder and the stress/strain state of the samples after fabrication. The small differences observed between the hysteresis portion of the loss in the samples compacted at 65 and 150°C may come from the effect of the compaction temperature on the stress/strain state in the materials. However, previous works [6] showed that the core losses were similar in iron–resin composites compacted at temperatures ranging from 22 to 140°C. Additional works have to be done to evaluate if the effect of the compaction temperature on the hysteresis portion of the loss is significant.

Fig. 1 shows that as frequency increases, the loss/cycle increases due to the rise of the eddy current portion. For example, the loss/cycle for sample A (ρ = 0.6 μΩ m) increases by 34% when frequency increases from 0 to 100 Hz. However, for samples having resistivities greater than 4 μΩ m, the eddy current loss remains low up to 100 Hz. For example, the increase in loss/cycle due to the eddy current losses for sample C (ρ = 4 μΩ m) is only 5% when frequency increases from 0 to 100 Hz and it is still lower for samples with higher resistivities. It is interesting to note that the eddy current losses in sample A (0.6 μΩ m) are twice that of sample B (1.2 μΩ m) since the eddy current portion of the loss is inversely proportional to the electrical resistivity of the samples.

As frequency exceeds a few hundred Hertz, the relation between the core loss/cycle and frequency is no longer linear as previously observed [2,7]. The method of separation of loss is valid as long as eddy-current shielding does not cause the flux near the middle of the specimen to lag too much behind the flux at the surface. At a given frequency, such a lag will cause the effective permeability to be substantially below that measured ballistically [8]. This is illustrated in Fig. 2 where the effect of resistivity and frequency on apparent permeability at 0.5 T is presented. Results show that eddy current shielding appears at lower frequency for low resistivity material. For sample A (ρ = 0.6 μΩ m), the permeability rapidly drops with the frequency while for sample C (ρ = 4 μΩ m), the permeability is stable up to 500 Hz. On the other hand, the permeability is significantly reduced at low
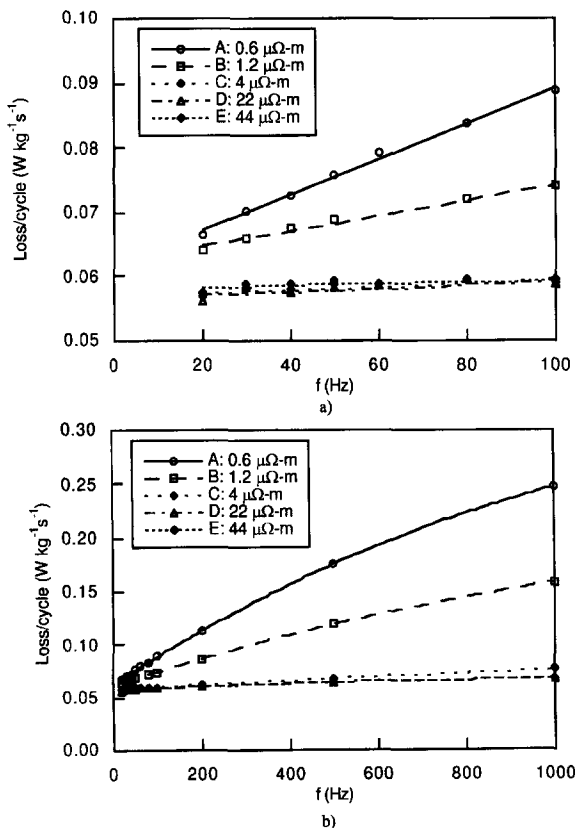

Fig. 1. Loss per cycle at 0.5 T versus the frequency; (a) 0–100 Hz; (b) 0–1 kHz.
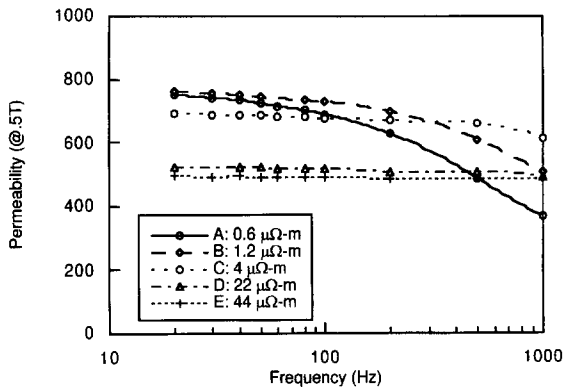
Fig. 2. Effect of electrical resistivity on the apparent permeability (at 0.5 T).

frequency ($f \to 0$ Hz in Fig. 2) when a small amount of resin is added to the iron powder.

According to these results, an electrical resistivity similar to the one generally observed in green iron powder compacts is sufficient to maintain low eddy current losses up to 1 kHz. In fact, previous works have shown that thin air gaps are created between the iron particles during the pressure release at the end of the compaction cycle. These air gaps have a high electrical resistivity which increases the resistivity of the compact (compared to wrought iron) [9]. It has been shown that at low frequency, a small amount of resin significantly reduces the permeability and is not required to reduce the core

loss (resin could nevertheless be used to improve the mechanical strength of the parts). However, since the eddy currents are proportional to the second power of frequency and inversely proportional to the electrical resistivity, the insulation has to be increased if a component has to be employed at medium/high frequency.

References

[1] IEEE Standard for Test Procedures for Magnetic Cores, IEEE Std 393, 1991.
[2] A. Campbell, H.C. Booth, D.W. Dye, Report on 5 samples of magnetic sheet material tested for total loss and hysteresis at the Phys.-Tech. Reichsanstalt and Nat. Phys. Lab, J. Inst. Elec. Eng. 48 (1912) 269.
[3] B. Weglinski, in: Reviews on Powder Metallurgy and Physical Ceramics, vol. 1, Freund Pub. House, Tel-Aviv, Israel, 1979, p. 79.
[4] L.P. Lefebvre, S. Pelletier, B. Champagne, C. Gélinas, Advances in Powder Metallurgy and Particulate Materials 1996, p. 20/47.
[5] L.P. Lefebvre, S. Pelletier, C. Gélinas, Presented at the 1997 Int. Conf. on Powder Metallurgy and Particulate Materials, Chicago, 29 June–2 July 1997.
[6] S. Pelletier, C. Gélinas, F. Chagnon, Advances in Powder Metallurgy and Particulate Materials, 1996, p. 20/63.
[7] C. Heck, Magnetic Materials and their Applications, Butterworth, 1974, p. 49.
[8] R.M. Bozorth, Ferromagnetism, IEEE Press, 1951, p. 782.
[9] L.P. Lefebvre, A.LeR. Dawson, S. Pelletier, Y. Deslandes, G. Pleizier, Particle bonding during heat treatment of green compacts intended for AC soft magnetic applications, Int. J. Powder Met., submitted.