Iron-resin composite materials for AC magnetic applications.

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Abstract: A broad range of P/M soft magnetic materials is now available for pulsed DC and AC applications. Some are produced from a pure iron powder in which the particles are insulated from each other by either a thin oxide layer and/or a thermoset resin. One of the most interesting attributes of these materials is the possibility to tailor their composition and processing to specifically meet application requirements. For example, in low frequency applications, the use of a coarse particle size iron powder admixed with a thermoset resin can give high apparent AC permeability and low core loss. In certain cases, pure iron powder without additives may be preferred in order to maximize the permeability. For higher frequency applications a more efficient insulation between iron particles and a finer particle size distribution are required to further reduce eddy currents.

This paper discusses the effect of composition and processing technique on the properties of iron-resin materials. Physical, mechanical and magnetic properties of specimens produced from these materials are presented together with their potential applications.

Introduction

Dielectromagnetics made of iron particles insulated from each other with dielectric materials are specifically designed for applications in alternating magnetic fields. These materials can be tailored to fill the performance gap between the properties of ferrites and those of laminated steels. Input design variables to be considered for the development of dielectromagnetics include application property requirements, material formulations, processing conditions as well as a good understanding of the property-application relationship. These factors have been taken into consideration for the development of iron-resin systems at QMP ?1?.

For example, a high purity and high compressibility water-atomized iron powder is the ferromagnetic material of choice for dielectromagnetic materials. A thermoset resin is also used to facilitate the shaping process, i.e., compaction followed by curing at low temperature. Moreover, there was a concern for mechanical properties of end-products that would not be affected by temperature and in general, thermosets fulfil that requirement better than thermoplastics. Finally, the processing of the materials was kept as simple as possible without sacrificing the property requirements: dry blending for low to medium frequency applications and wet blending for high frequency applications. All these factors combined to give the customer the lowest cost product with the best performance.

Currently, three generic families of materials are available that cover a broad range of frequencies from 50-60 Hz up to about 1 MHz. The main differences lie in the particle size of the base iron powder, in the quantity of thermoset resin and in the fabrication process. This paper summarizes the differences between these three families of materials, their properties and their potential applications.

Low-to-medium frequency material

This iron-resin material called ATOMET EM-1* was specifically developed to compete with low carbon steel laminations currently used in low to medium frequency applications (up to 50 kHz). It is composed of a high purity and high compressibility, coarse water-atomized iron powder (65 to 250 µm) mixed with a thermoset resin powder. In the course of an extensive development program, it was found that 0.8% resin in the mix was the optimum level to achieve high mechanical strength and good magnetic properties ?1?. However, the composition of the material can easily be tailored to meet the specific application requirements. Note that no lubricant is added to the iron/resin mix because it decreases the relative density or effective quantity of iron in the pressed parts and consequently negatively affects the magnetic properties. The quantity of organics (resin or lubricant) has to be kept as low as possible in order to get the most out of the ferromagnetic properties of iron.

A typical iron-0.8% resin mix has an apparent density and Hall flow rate of 2.75 g/cm^3 and 28 s/50 g respectively. The compressibility of the powder mix is very good and densities as high as 7.30 g/cm^3 can be reached at a compacting pressure of 800 MPa. After pressing, the parts are usually cured in air to cross-link the resin and achieve the maximum possible strength. Note that the density is not affected by the curing treatment. However, the temperature of the curing treatment has an impact on the mechanical strength and electrical resistivity.

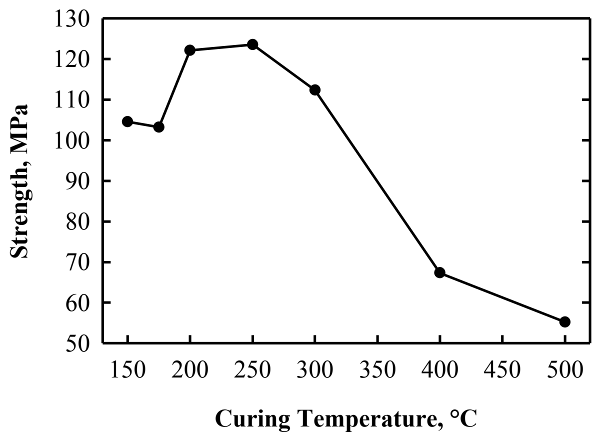

Figure ***1*** *Effect of curing temperature on* strength *of iron/0.8% resin composites pressed at 620 MPa and 65°C and cured for 30 minutes in air.*

The transverse rupture strength evaluated according to the MPIF Standard 15 for iron/0.8% resin bars pressed at 620 MPa/65°C and cured in air for 30 minutes at different temperatures is illustrated in Figure 1. The strength increases with the curing temperature to reach a maximum of about 120 MPa in the 200°C to 250°C temperature range. Beyond 300°C, the strength decreases continuously which likely corresponds to a deterioration of the resin and eventually to its burn-off. It is however worth noting that the value of about 55 MPa at 500°C is much higher than the green strength of the composite material before curing, which is about 25 MPa.

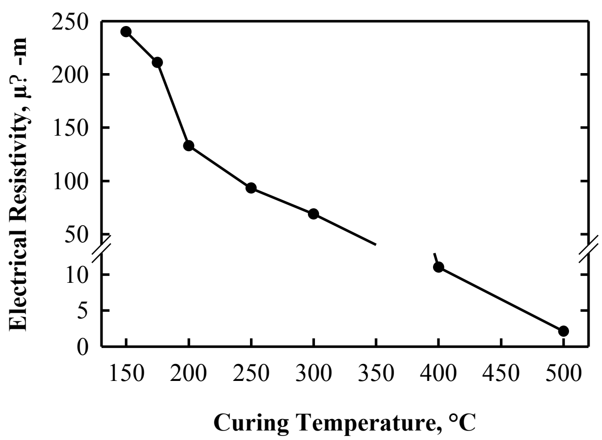

Figure 2 *Effect of curing temperature (30 min curing) on electrical resistivity of iron/0.8% resin composites pressed at 620 MPa/65°C.*

The electrical resistivity reflects the degree of insulation between the iron particles and is necessary to minimize eddy currents. As illustrated in Figure 2, the resistivity of iron/0.8% resin bars pressed at 620 MPa/65°C and cured for 30 minutes decreases with the curing temperature. At 150°C, the resistivity value of about 250 µ? -m is similar to the value after pressing and before curing. This value decreases continuously with an increase in the curing temperature down to about 2 µ? -m at 500°C. However, at low frequency around 60 Hz and depending on the shape factor of the part application, experiments showed that a resistivity in the 5 to 20 µ? -m range is sufficient to shield the eddy currents [2,3].

The DC magnetic properties of the material are an important input characteristic in the designing of parts for AC applications. Typically, for an

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iron/0.8% resin composite pressed to 7.20 g/cm³ and cured at 200°C for one hour in air, a magnetization of 1.38 T, a maximum permeability of 290 and a coercive field of 420 A/m are measured in DC at an applied field of 11940 A/m (150 Oe).

The core loss characteristics of this iron/0.8% resin material at 60 and 400 Hz are given in Figure 3 together with those of a reference low carbon steel sheet lamination (AISI 1008) as well as those of the same iron/resin material cured at a higher temperature (400°C for 30 minutes) in order to minimize the hysteresis loss. The curing treatment at 400°C partially stress relieves the material thus decreasing the hysteresis loss and consequently the total core loss [2,4,5]. Indeed, at low frequency, the hysteresis loss counts for more than 90% of the total core loss in these composite materials [6]. For example, at 60 Hz and 1 T of magnetization, the iron/resin material cured at 400°C has a core loss of 9.9 W/kg which represents a decrease of 11.6% compared to the material cured at 150°C and is similar to that of the 1008 steel lamination. At 400 Hz and 1 T, the two composite materials cured at low and high temperature show the same core loss and perform much better than the reference lamination: 85 W/kg versus 180 W/kg. These results show the advantage to cure the composite material at high temperature for applications at 60 Hz but not for applications at 400 Hz because the beneficial effect of the stress relief of the material (decrease of the hysteresis loss) is canceled by the decrease in resistivity (increase of eddy currents).

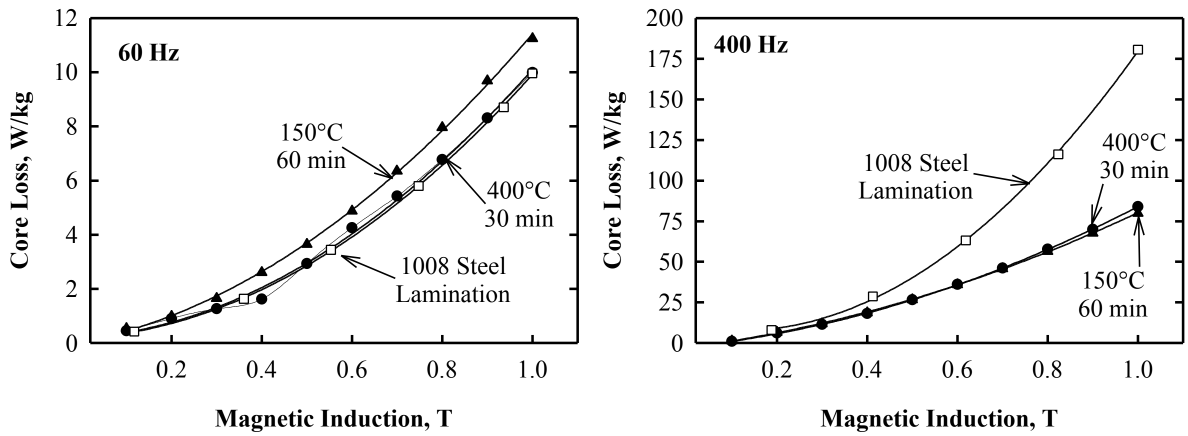

Figure 3 *Core loss comparison at 60 Hz and 400 Hz between a reference low carbon steel (AISI 1008) and iron/0.8% resin composites pressed at 620 MPa/65°C and cured at 150°C and 400°C.*

In cases where the use of an external lubricant is not possible or not practical and where the requirements for the strength are not as important, an internal lubricant can be added to the composite mix. The properties after pressing and curing at 200°C for 60 minutes are very similar to those of the ATOMET EM-1 composite material except for the strength which is slightly lower (75 MPa).

These low-to-medium frequency materials may replace existing laminated parts without modification (drop-in) but much better results may be obtained by redesigning the parts to take advantage of the isotropic properties of these iron-resin composite materials. They can be used in small motors, alternators and generators, ignition cores, speed sensors, ballasts, relays, voice coil housings, switched reluctance motors and DC brushless motors. They show stable properties in applications subjected to temperature variations such as devices in under-the-hood and indoor automotive applications [7,8].

High permeability material

Following the development of a first iron-resin material for low to medium frequency applications, a need for a material with a high permeability and low loss characteristics at 60 Hz appeared. As mentioned above, at low frequency, total losses are dominated by the hysteresis loss. Moreover, the electrical resistivity of the material does not need to be very high to minimize eddy currents at 60 Hz (5 to 20 µ? -m). These considerations led to a modification of the material and processing system in order to achieve the desired properties: substitution of the resin by a lubricant and low temperature thermal treatment of the parts. Indeed, because the magnetic properties are mainly dependant on the properties of the iron powder (particle size, purity, compressibility, …) and the degree of needed insulation is low at 60 Hz, it is possible to use an internal lubricant instead of a resin, thus facilitating the pressing. In fact, depending on the type and quantity of lubricant and the type of atmosphere and temperature of the thermal treatment, materials with high permeability, low core loss and adequate strength can be obtained [4,5].

For example, high permeability materials can be made by pressing pure iron with 0.75% of a zinc stearate (ZnSt) or ethylene bis-stearamide (EBS) lubricant powder at a density of 7.20 g/cm^3 and treating the parts in nitrogen at 450°C for 30 minutes. The ZnSt containing mix will give specimens with a higher electrical resistivity (more residue after the thermal treatment) than the EBS containing mix which will affect most of the magnetic properties. The typical properties measured on these high permeability iron/lubricant materials are compared in Table I with those of the regular iron/0.8% resin composite material cured at 200°C for 60 minutes in air.

Table I *Characteristics and typical properties of the high permeability material compared with those of the iron/0.8% resin composite material (all samples pressed at 7.20 g/cm³).*

	High permeability material		ATOMET EM-1
	Iron/0.75% EBS	Iron/0.75% ZnSt	Iron/0.8% resin
Applications	60 Hz		60 to 50000 Hz
Thermal treatment	450°C/30 min in N_2		200°C/60 min in air
Resistivity, µ? -m	3	9	150
Strength (TRS), MPa	55	30	120
DC properties at 11940 A/m:			
B_{max}, T	1.40	1.42	1.38
μ_{max}	400	320	290
H_c, A/m	320	314	420
AC properties (60 Hz):			
Core Loss at 1 T, W/kg	10.3	9.0	11.2
μ_{max}	620	520	400

The DC and AC maximum permeabilities of the iron/lubricant materials are much higher than those of the iron/resin composite: 10% to 38% higher in DC and 30% to 55% higher in AC. On the other hand, in spite of a much lower electrical resistivity, the core loss of the two high permeability materials at 60 Hz is low. This is mainly due to the beneficial effect of the thermal treatment that stress relieves the material thus decreasing the hysteresis loss (higher permeability and lower coercivity). In the case of the ZnSt containing material, the combination of this beneficial effect with a relatively high electrical resistivity of 9 µ? -m decreases the core loss by 20% compared to the iron/resin material. The strength of the high permeability materials is relatively low but it can be easily increased up to 100-110 MPa by impregnating the treated parts with a resin [4,5,7].

These high permeability materials may be used in applications similar to those of the low-to-medium frequency material. They are especially suitable where DC characteristics are important (high permeability and low coercivity) and the mechanical strength less demanding like in ignition cores, inductors, flux carriers and relays.

High frequency material

Material and property requirements differ for high frequency AC magnetic applications. For instance, core loss and initial permeability are the most important property requirements to consider when selecting materials for high frequency applications. As frequency increases, the relative importance of eddy current losses in total core loss increases and most of the improvement in core loss at high frequencies comes from improvements in eddy current shielding. The relationship between material characteristics and eddy current losses (P_e) is given by the following equation:

$$P_e \; ? \; \frac{K_e B^2 f^2 d}{?} \qquad (1)$$

where K_e is a constant, B is the magnetic induction, f is the frequency, d is the shortest dimension perpendicular to the flux path and ? is the electrical resistivity. The last two parameters are materials characteristics that can be adjusted to meet the application requirements. In the case of dielectromagnetics, d and ? can be modified by varying the degree of insulation between the iron particles and by varying their particle size. In accordance, the iron-resin material system was adapted to fulfil these requirements [9].

The material system is composed of a fine high purity and high compressibility water-atomized iron powder wet mixed with a thermoset resin powder. The process consists of dissolving the resin in an adequate quantity of solvent, spraying the solution onto the iron particles, mixing and drying. Here again the composition of the composite material can be tailored to meet specific property requirements. For instance, the fineness of the iron powder and the quantity of resin can be varied. The effect of varying these parameters on the initial permeability measured at 0.5 mT and the total losses calculated at 1 mT are given in Figure 4 and 5 respectively. The two graphs also show the performance of a low-to-medium frequency material for comparison purposes. This reference composite material contains an iron with a particle size typical of a water-atomized powder (< 250 µm) dry mixed with 0.8% resin. The high frequency materials contain the same iron powder screened to remove the particles larger than 75 µm or 45 µm and wet mixed with three levels of resin. Their typical resistivity ranges from 1000 to 3000 µ? -m.

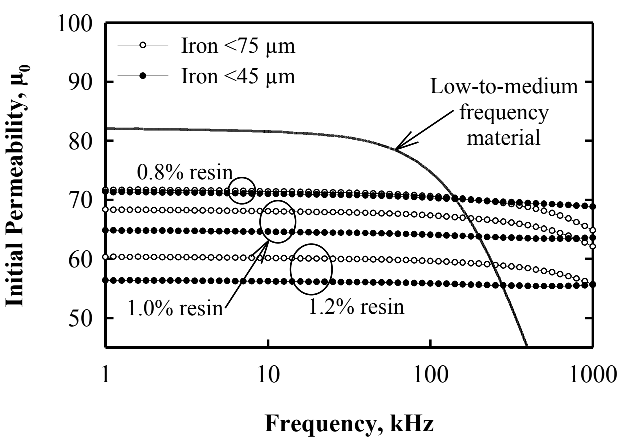

Figure 4 *Effect of iron particle size and resin content on the initial permeability at 0.5 mT of high frequency materials and a low-to-medium frequency material.*

In Figure 4, the level and stability of initial permeability with respect to frequency gives a good indication of the domain of applications of these materials. The reference low-to-medium frequency material has a high initial permeability with a value of 82 which is constant up to about 50 kHz and then decreases rapidly. On the other hand, the high frequency materials have a lower permeability but much more constant with the frequency up to hundreds of kHz. A finer iron powder gives a lower permeability which is more stable with respect to frequency while a higher resin level decreases the density of the material and consequently the initial permability.

The domain of applications of these two types of materials is also in evidence in Figure 5 where the total losses for the low-to-medium frequency material are almost one order of magnitude higher than those of the high frequency materials. The inset also shows that losses decrease with a decrease of the iron particle size and an increase of the resin content. Typically, there is a decrease of about 30% in losses by decreasing

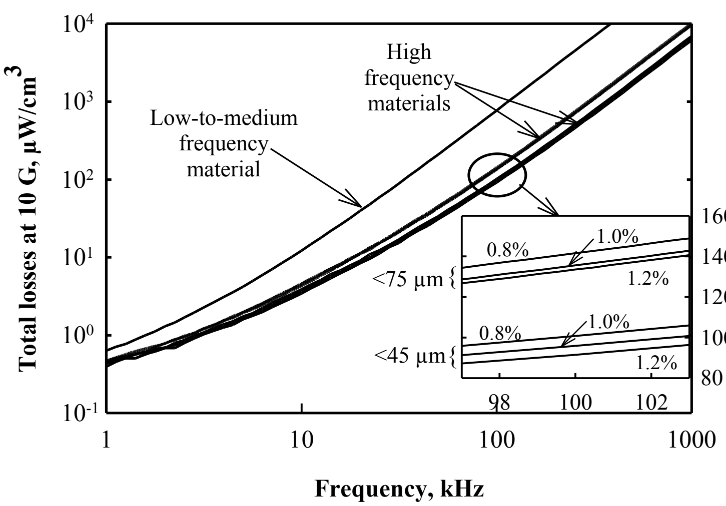

Figure 5 *Total losses at 1 mT of high frequency materials compared with a low-to-medium frequency material. The inset at 100 kHz shows the effect of the iron particle size and resin content.*

the iron particle size from 75 µm down to 45 µm.

These materials are designed for high frequency inductors, ballasts, magnetic fluids, transformer cores, etc.

Conclusion

It is now possible with new P/M material systems to break new ground in the area of AC magnetic applications. Depending on the frequency range of the application, the material system can be tailored to meet the specific requirements. For instance, high permeability materials are composed of a high purity coarse iron powder with a lubricant and produce parts with a high induction, high permeability and low core loss at 60 Hz. By replacing the lubricant with a resin, low-to-medium frequency materials such as ATOMET EM-1 give parts with a higher strength and a low core loss at frequencies up to 50 kHz. Finally, by modifying the process and decreasing the iron particle size in order to increase the electrical resistivity, high frequency materials produce parts with low core loss at frequencies up to 1 MHz. As these AC magnetic materials gain acceptance by designers and are tried in specific applications, they are going to find a niche in this field [10].

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