LUBRICATED IRON POWDER MIXES FOR LOW FREQUENCY SOFT MAGNETIC APPLICATIONS

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ABSTRACT

Iron-lubricant mixes may be processed to near-net-shape soft magnetic components using powder-metallurgy techniques. The components have isotropic magnetic and thermal properties and may be shaped into complex geometries using conventional compaction techniques. After compaction, the components are thermal treated at moderate temperature (600°C) to burn out the lubricant, relieve the stresses induced during pressing and reduce the hysteresis loss.

Depending on the application, the material properties may be tailored by varying the lubricant content in the mixes. By increasing the lubricant content from 1% to 2.5%, the electrical resistivity increases (2-5 μΩ-m) while the thermal conductivity (18-9 W/m-K), the magnetic permeability (250-110) and the core loss (11.0-7.3 W/kg) decrease.

1. INTRODUCTION

Soft magnetic components can be produced to near-net-shape using powder metallurgy (P/M) techniques. Depending on the application, the choice of the material and the processing conditions may greatly differ. For DC magnetic applications, the components are generally sintered. For AC applications, the magnetic particles are insulated from each other and the components are not sintered to provide materials with an electrical resistivity sufficient to maintain low eddy-current losses. Moreover, the parts are usually not sintered in order to prevent the destruction of the electrical insulation.

A very simple route to fabricate AC soft magnetic components is to press iron-lubricant mixes and treat the components at a moderate temperature [1,2]. The lubricant eases the compaction and ejection of the components and provides the insulation between the magnetic particles. The thermal treatment at moderate temperature burns out the lubricant and relieves the internal stresses induced during compaction, which significantly increase the hysteresis loss. After thermal treatment, the material may have electrical resistivity sufficient for applications at 60 Hz. The components may be resin impregnated afterwards to increase their mechanical strength and provide an insulative and protective coating if required.

The properties of material may be easily modified by changing material composition and processing conditions. The operating frequency is a key parameter for the selection of the material and processing conditions in order to obtain the optimum properties for a specific application. For example, permeability is inversely proportional to dielectric content while the electrical resistivity increases with the dielectric content [3]. For most applications, the dielectric content must be minimal to maintain high permeability, while sufficient to maintain low eddy-currents and complete magnetization of the magnetic material at the operating frequency.

The objective of this study is to evaluate the effect of the lubricant content on the electrical, magnetic, thermal and mechanical properties of pressed, thermal-treated and resin-impregnated specimens for low frequency soft magnetic applications.

2. EXPERIMENTAL PROCEDURE

A high purity, water-atomized iron powder[*] was used in these experiments. The fines were screened out to leave a powder with particles between 75 µm and 250 µm (-60 +200 mesh). The powder was mixed with 1 to 2.5 weight % zinc stearate in a laboratory V-type blender for 30 minutes. Hall flow rate and apparent density of the mixes were evaluated according to MPIF Standards 03 and 04.

Rectangular bars (3.175 x 1.27 x 0.635 cm) and rings (OD = 5.26 cm, ID = 4.34 cm, h = 0.635 cm) were pressed at 620 MPa (45 tsi) in a double action floating die at room temperature. Peak ejection forces were measured on the rectangular bars and peak ejection pressures were calculated by dividing the ejection force by the lateral surface area of the compact in contact with the die walls. After compaction, the specimens were heated in a tube furnace at 600°C in argon for 5 minutes to burn out the lubricant. The heating and cooling rates were 10°C/min and 5 °C/min respectively. The thermal-treated specimens were resin impregnated under vacuum with an epoxy resin to increase their mechanical strength. After impregnation, the specimens were cured (75°C) to cross-link the resin. Three bars and three rings were prepared for each experimental condition.

Density, transverse rupture strength (TRS) and electrical resistivity were measured on the rectangular bars. Transverse rupture tests were made according to MPIF Standard 41. The electrical resistivity was evaluated using a four-point contact probe (0.8 cm between contact points) and a micro-ohmmeter[1] adapted for this application. Five readings were taken on the top and bottom faces of each bar and averaged. Side and thickness effects were taken into account in the electrical resistivity calculations.

Thermal conductivity was evaluated on 8 x 8 x 1 mm specimens (cut from TRS bars) using normal diffusivity measurements (flash method) described elsewhere [4]. The thermal conductivity was calculated using the following equation:

$$K = \alpha\ \rho\ C_p$$

[*] ATOMET 1001HP supplied by QMP.
[1] UltraOptec, model: PM450

where α is the thermal diffusivity, ρ is the density and C_p the thermal capacity of the specimens. The thermal capacity of iron (22.2 J/mole-K) was used for the thermal conductivity calculations.

The DC magnetic properties were evaluated for every experimental condition on one series of rings. The core losses at 60 Hz were evaluated for the three duplicated rings per experimental condition using two different commercial hysteresisgraphs. The values at 1T (2.5% lubricant) and 1.5T (all mixes) were extrapolated for one hysteresisgraph using linear regressions extracted from "core loss vs induction" graphs plotted on a log-log scale.

3. RESULTS

The lubricant content does not significantly affect the apparent density of the mixes. The measured apparent density varies between 2.98 and 3.01 g/cm^3 for all the mixes. The flow rate slightly deteriorates, from 28 to 31 s/50 g, when the lubricant content increases from 1 to 2.5%. As expected, increasing the amount of lubricant in the mixes reduces the pressure required to eject TRS bars, as shown in Figure 1. Even for the mix containing 1% lubricant, a relatively low peak ejection pressure (25 MPa) was obtained. The peak ejection pressure decreases with an increase of the lubricant content, and reaches 16 MPa (1.2 tsi) for the mix containing 2.5% lubricant.

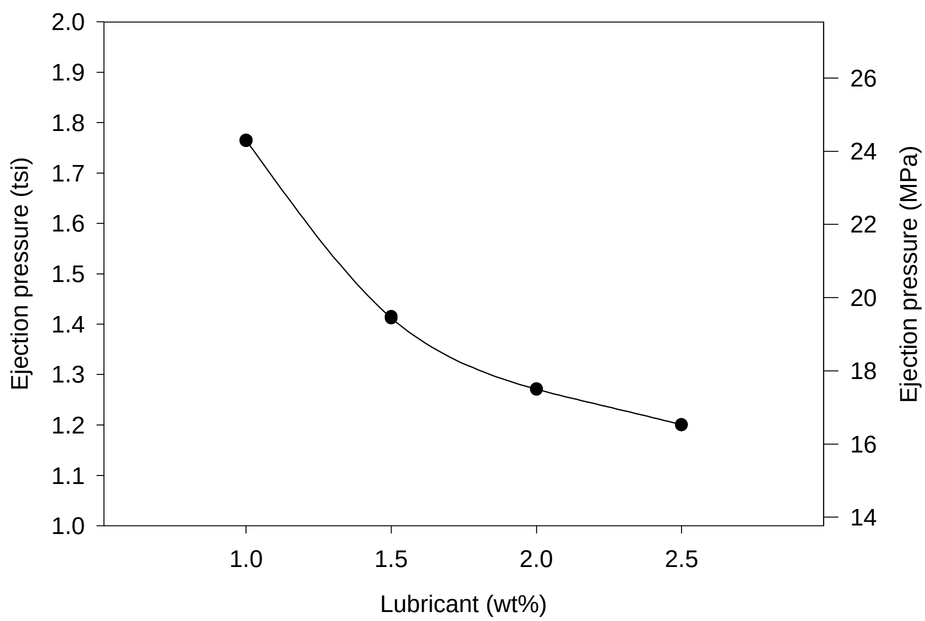
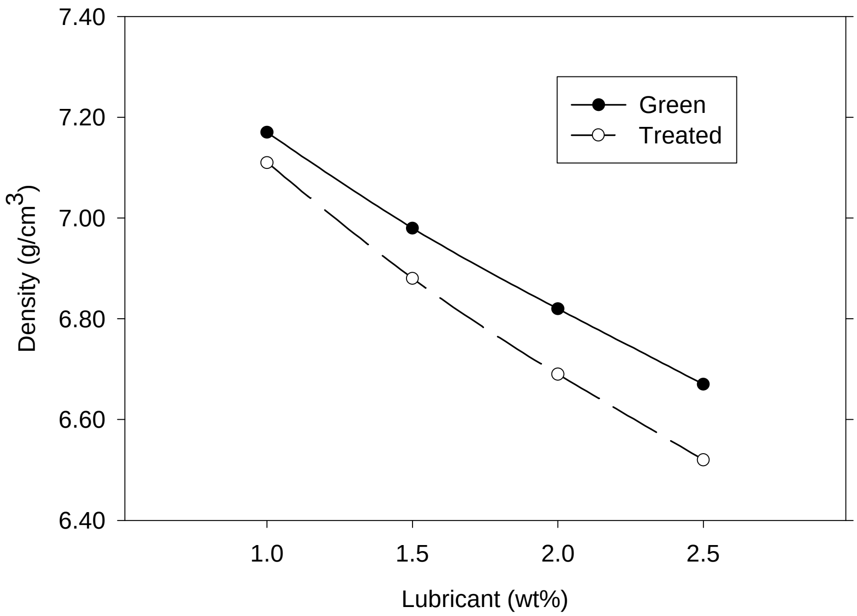


Figure 1. Effect of lubricant content on peak ejection pressure of TRS bars pressed at 620 MPa (45 tsi).

Figure 2 shows the effect of the lubricant content on the density and electrical resistivity of the bars, as pressed and after a thermal treatment at 600°C. The density of the green specimens (Figure 2a) decreases from 7.15 to 6.65 g/cm^3 with an increase of the lubricant content from 1 to 2.5%. During the thermal treatment at 600°C, the lubricant burns out and a decrease in density between 0.10 and 0.15 g/cm^3 occurs.



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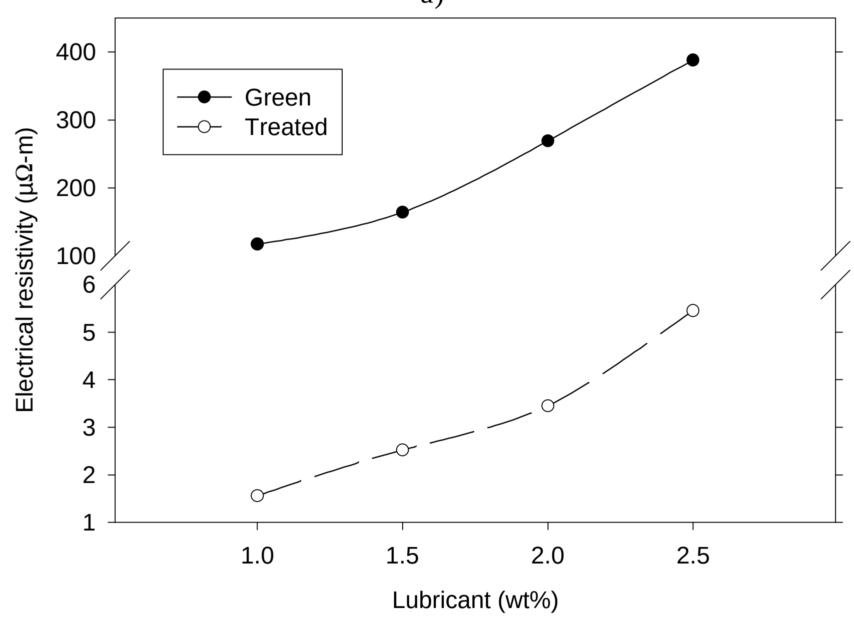

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Figure 2. Effect of lubricant content on a) density and b) electrical resistivity of TRS bars before and after a thermal treatment at 600°C.

The electrical resistivity of the green specimens (Figure 2b) increases from about 100 to 400 μΩ-m when the lubricant content increases from 1 to 2.5%. As expected, the lubricant acts as an insulator between the iron particles and increases the electrical resistivity of the material. During the thermal treatment, many contacts are created between the iron particles, which decreases the electrical resistivity below 5 μΩ-m. This resistivity value is nevertheless higher than that of bulk iron (0.1 μΩ-m) or iron-silicon alloys (~0.5 μΩ-m)[5]. This level of residual resistivity suggests that particle interfaces are still insulated after the thermal treatment. This insulation is provided by air gaps, oxides and lubricant decomposition products between the iron particles. Since the electrical resistivity is proportional to the lubricant content, it is thus possible, to a certain extent, to adjust the electrical resistivity of the material by varying the lubricant content in the mixes used to fabricate the test rings.

The effect of the lubricant content on the thermal conductivity of thermal-treated bars after resin impregnation is shown in Figure 3. The thermal conductivity decreases from 19 to 9 W/m-K with an increase of the lubricant content from 1 to 2.5%. Note that these values are significantly higher than those measured perpendicularly to laminations in stack assemblies [6]. Moreover, thermal conductivity in these P/M parts is isotropic and heat can be extracted uniformly in all directions. This represents a significant technical advantage over stack assemblies where heat is extracted mainly at lamination edges. This gives more freedom in the design of magnetic components, which can dissipate the heat more effectively.

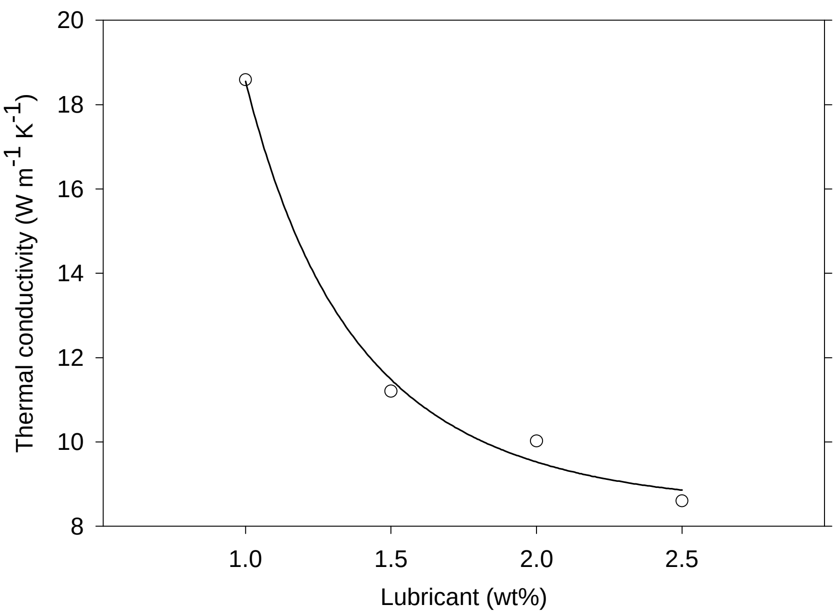
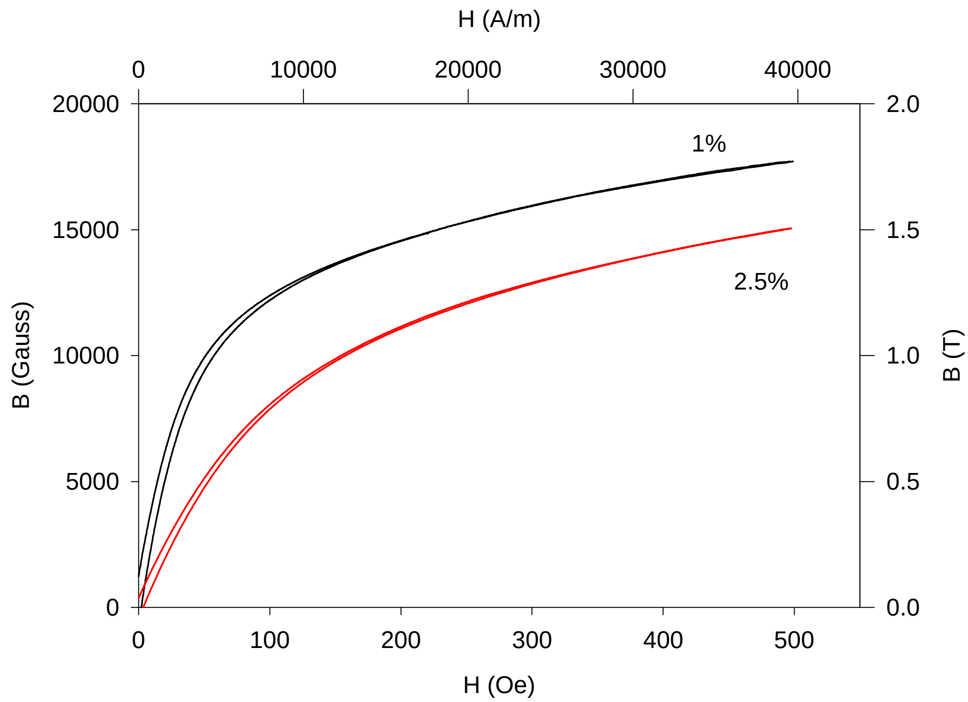


Figure 3. Effect of the lubricant content on the thermal conductivity of thermal-treated bars after resin impregnation.

The mechanical strength of the specimens after thermal treatment and resin impregnation is higher than 110 MPa (16000 psi). These strength values are similar to those obtained with typical iron-resin composites cured at 200°C [3] and are adequate for many AC soft magnetic applications.

The DC magnetization loops of two thermal-treated specimens with two different lubricant content (1% and 2.5%) are presented in Figure 4a. The amount of lubricant in the mix affects the shape of the curve. When the lubricant content increases, the magnetization loop is sheared and the magnetization and permeability decrease. The shearing is associated to the increase in the thickness of the distributed air-gap (pores between iron particles) in the material when the lubricant content increases. The corresponding DC maximum permeability is shown in Figure 4b. The permeability decreases from 260 to 110 with an increase of the lubricant content from 1 to 2.5%.

The coercive force H_c, on the other hand, was not significantly affected by the lubricant content with a value around 225 A/m (2.8 Oe) for all mixes. Indeed, coercive force mostly depends on the composition and structure of the magnetic phase and is not affected by the presence of air gaps. It is worth mentioning that the coercive force before the thermal treatment at 600°C was around 400 A/m (5.0 Oe). As previously reported, the reduction of the coercive force is attributed to the partial stress relief that occurs during the thermal treatment [7].



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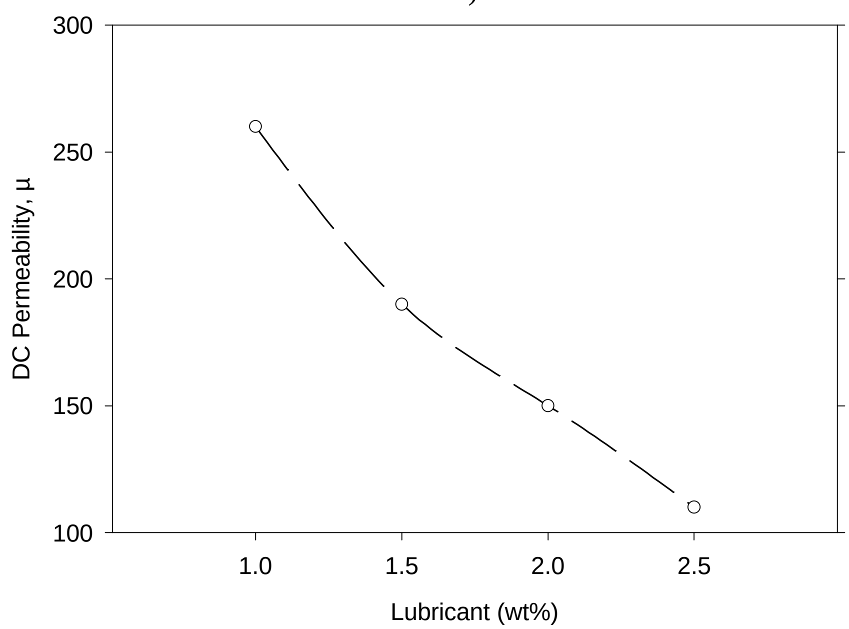

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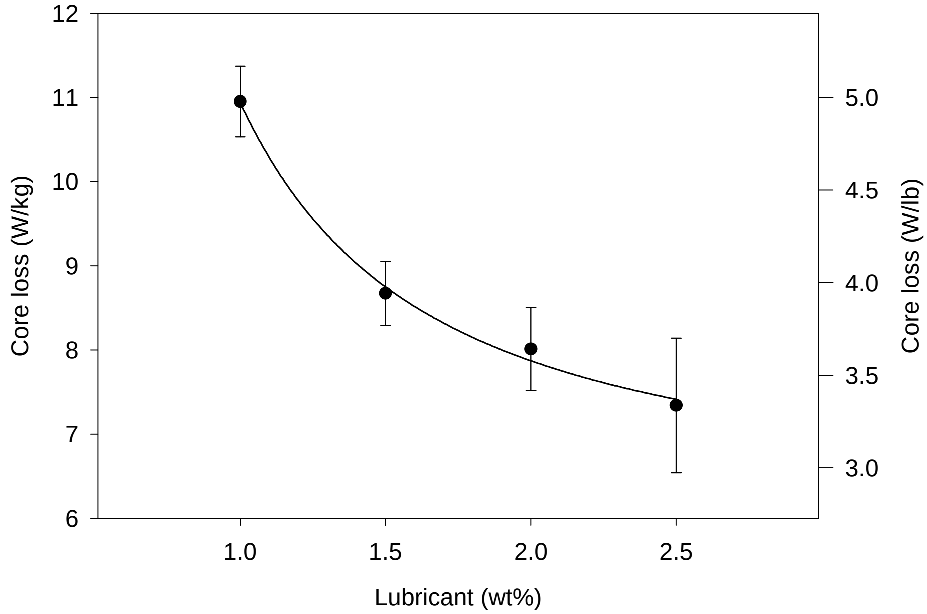
Figure 4. Effect of lubricant content on DC magnetic properties: a) DC magnetization curves and b) DC maximum permeability.

The effect of the lubricant content on the core losses at 60 Hz is illustrated using two different ways in Figure 5. The two graphs (5a and 5b) show that an increase of the lubricant content decreases the losses at 60 Hz. Moreover, the decrease is more important when the magnetization increases as reported in Table I for the specimens pressed from the mixes containing 1 and 2% lubricant.



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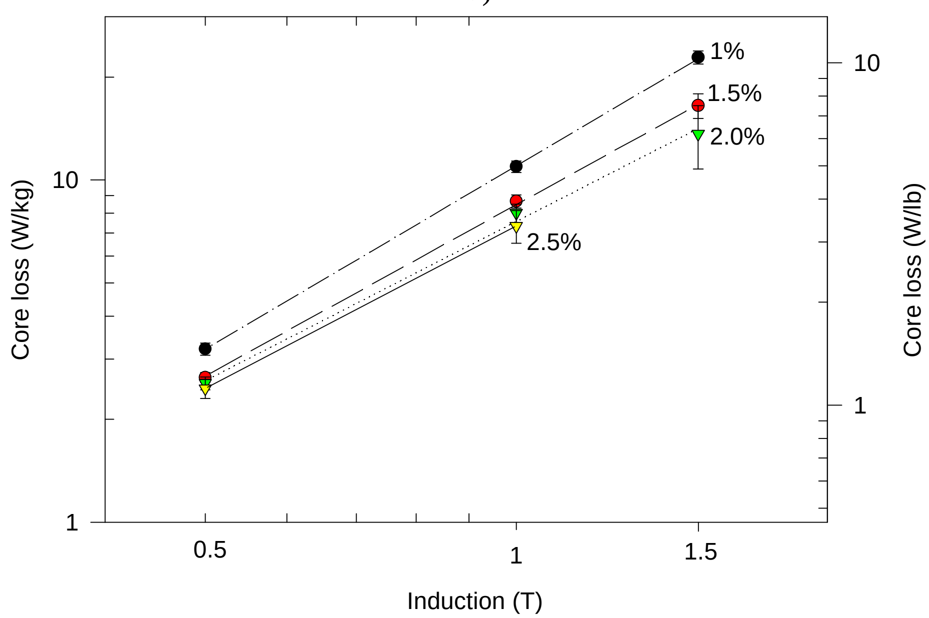

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Figure 5. Effect of lubricant content on core loss at 60 Hz: a) for an induction of 1 T and b) at different inductions.

Table I
Core loss at 60 Hz in W/kg (W/lb) for specimens pressed
from mixes containing 1 and 2% lubricant.

Magnetization	1% lubricant	2% lubricant	Improvement
0.5 T	3.2 (1.4)	2.6 (1.2)	19%
1.0 T	11.0 (5.0)	8.0 (3.6)	27%
1.5 T	22.8 (10.4)	13.6 (6.2)	42%

The decrease in core loss is mainly attributed to the increase of electrical resistivity (Figure 2b) that reduces the eddy currents. The minimum core loss was obtained for the material containing 2.5% lubricant with a value of 7.3 W/kg (3.3 W/lb) at 1 T. Note that the losses at 60 Hz in these thermal-treated specimens are lower than those of typical iron-resin composites cured at a lower temperature [7]. As previously mentioned, this is due to the fact that the stresses that are induced in the material during the compaction step are partially relieved during the thermal treatment thus reducing the hysteresis portion of the total loss.

Thermal treatment also reduces the electrical resistivity of the material. It has already been reported that heating the specimens at lower temperatures will lead to higher electrical resistivity [2]. However, the decrease in hysteresis loss and total loss will not be as signifiant if the specimens are heated at lower temperatures.

4. CONCLUSION

In this study, lubricated iron mixes were used to prepare specimens with characteristics adequate for AC soft magnetic applications at 60 Hz. The iron/lubricant mixes were pressed at 620 MPa (45 tsi), treated thermally at 600°C in argon and impregnated with a resin. It was observed that the thermal treatment partially relieved the internal stresses induced during compaction and reduced the hysteresis portion of the losses. The impregnation increased the strength of the specimens to values higher than 110 MPa (16000 psi), which is sufficient for many soft magnetic applications.

The results also indicate that the thermal, electrical and magnetic properties of the specimens may be adjusted to a certain extent by varying the lubricant content in the mixes. For the iron/lubricant system studied here, an increase of lubricant content from 1.0 to 2.5% had the following effects on the properties of the thermal treated and resin impregnated specimens:

- a reduction of thermal conductivity from 19 to 9 W/m-K;
- an increase of electrical resistivity from 2 to 5 μΩ-m;
- a reduction of DC maximum permeability from 250 to 110;
- a reduction of core loss at 60 Hz and 1 T from 11.0 to 7.3 W/kg.

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