HIGH PERMEABILITY IRON P/M MATERIALS FOR LOW FREQUENCY MAGNETIC APPLICATIONS.

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ABSTRACT

Advantages of P/M for the manufacturing of soft magnetic components include isotropic magnetic and thermal properties, nearly wasteless production and ease of fabrication. For DC applications, sintered materials are generally used while for AC applications, electrically insulated particles may be used to maintain low core loss.

High purity water-atomized iron powder is particularly well suited for AC soft magnetic applications. An appropriate processing of these powders may lead to parts having high permeability, low losses at low frequency combined with adequate mechanical strength. This paper presents the effect of compaction temperature and a thermal treatment on the mechanical and magnetic properties of parts fabricated with iron powder intended for low frequency magnetic applications.

1. INTRODUCTION

Powder metallurgy (P/M) offers many advantages for the production of soft magnetic components intended for AC applications. P/M allows the fabrication of near net shape components with isotropic thermal and magnetic properties [1]. The thermal conductivity of these materials is higher than the conductivity measured perpendicularly to laminated assemblies [2]. Isotropic thermal properties allow more liberty in the design of components since heat can be extracted from anywhere on the part in contrast to laminated stack assemblies where heat is extracted mostly at the lamination edges. Furthermore, isotropic magnetic properties allow the design of parts with a 3-D magnetic field distribution. These characteristics open opportunities to design new components with improved performance.

P/M soft magnetic components are usually fabricated by compacting a powder or a powder mix to near net shape and heat treating (curing/sintering) the parts to obtain the desired mechanical and magnetic properties. Up to now, pressed and sintered iron powders have been extensively used to fabricate parts for DC applications. For AC applications, a resin is generally added to the magnetic powder that provides both the electrical insulation and mechanical strength of the pressed parts. Iron-resin composites (dielectromagnetics) are presently available industrially for these applications.

The apparent permeability and core loss are among the important magnetic properties of dielectromagnetics for low frequency AC applications. Permeability (μ = B/H) is a measure of the ability of a material to be magnetized and is defined as the ratio of the induced magnetic field B on the applied field H. The permeability of dielectromagnetics is strongly influenced by the effective packing of the magnetic powder. Dielectrics generally used in dielectromagnetics have a permeability close to that of air and act as a distributed air gap in the material [3]. The permeability of dielectromagnetics is thus significantly reduced as the resin content (or air gap length) increases [4]. To obtain parts with a high permeability, the resin content should then be kept as low as possible. On the other hand, warm pressing increases the effective packing of iron powder [5] and consequently the permeability of iron powder compacts intended for soft magnetic applications since ductility is increased and strain hardening reduced as temperature increases [6].

Core loss is commonly subdivided into two components: the hysteresis (P_h) and the eddy current losses (P_e). These losses may be expressed as followed [7]:

$$P_{tot} = P_h + P_e \tag{1}$$

$$P_h = f \oint H dB \tag{2}$$

$$P_e = \frac{K_e B^2 f^2 d^2}{\rho} \tag{3}$$

where f is the frequency, H is the applied field, B is the magnetic induction, K_e is a constant, ρ is the electrical resistivity and d is the shortest dimension perpendicular to the magnetic flux path (mean powder diameter in dielectromagnetics). The hysteresis loss corresponds to the energy dissipated by the domain wall movement during cyclical magnetization [8] and is mainly affected by the chemical composition and the structure of the material [9]. Eddy current losses are generated by currents induced when a conducting material is exposed to an alternating magnetic field [10]. Eddy current losses depend on the powder particle size and the resistivity of the material (equation 3). The relative importance of eddy current losses on total core loss increases as the frequency increases.

Green compacts fabricated from pure iron powder without any additive have high density and high permeability compared to iron-resin composites. Furthermore, compared to sintered iron in which the oxides have been reduced and metallurgical contacts created between the iron powder, green compacts have a much higher resistivity due to the natural surface oxide present at the surface of the iron powder [11]. However, the strength of green compacts is generally low and not acceptable for most of the applications. However, parts can be strengthened externally using tape or tough coating [12] or can be impregnated to increase their mechanical strength [13].

Based on these considerations, a study was undertaken in order determine material processing conditions that would maximize the apparent permeability and mechanical strength while maintaining an adequate resistivity for low frequency magnetic applications. In this paper, the effect of compacting temperature and the effect of low temperature heat treatment (one hour at 175°C in air) are evaluated. The mechanical and AC magnetic properties of specimens pressed from a pure iron powder are presented.

2.EXPERIMENTALPROCEDURE

A high purity water-atomized iron powder designed for magnetic applications (ATOMET 1001HP) was used in these experiments. The particle size distribution of the powder is nominally less than 250 µm. There was no lubricant or additive in the powders and die walls were lubricated using a graphite spray prior to each compaction.

Rectangular bars (3.175 x 1.27 x 0.635 cm) and rings (OD = 5.26 cm, ID = 4.34 cm, t = 0.635 cm) were pressed at 620 MPa (45 tsi) in a double action floating die at different temperatures. The density, transverse rupture strength (TRS) and electrical resistivity were measured on five bars before and after a thermal treatment at 175°C for one hour in air. The density was calculated from the weight and physical dimensions of the bars. Transverse rupture strength 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 adapted for this application. Side and thickness effects were taken into account in the resistivity calculations. Five readings were taken on the top and bottom faces of each TRS bar and averaged. AC magnetic properties (apparent permeability and core loss) were measured at 60 Hz and 400 Hz at a magnetization of 0.5 T using a ACT/SMT-500 computer-automated magnetic hysteresisgraph. Rings were wound with 250 primary turns of #24 gauge copper wire and 250 secondary turns of #30 gauge copper wire.

3.RESULTS AND DISCUSSION

The effect of compaction temperature and heat treatment (1h at 175°C in air) on the density of bars pressed from pure iron powder at 620 MPa (45 tsi) is presented in Figure 1. The density increases from approximately 7.27 g/cm^3 to 7.38 g/cm^3 when the compaction temperature increases from 65°C to 300°C. This increase is related to the reduction of the yield strength and strain hardening as the compaction temperature increases. It is known that the yield strength is strongly influenced by temperature in c.f.c. crystals such as iron and that strain hardening is slightly reduced when compaction temperature increases [14]. There are practically no differences between the density of the samples before and after the heat treatment. The heat treatment is done at low temperature and practically no densification occurs.

Figure 2 presents the effect of compaction temperature and a thermal treatment at low temperature on the resistivity of the iron compacts. The resistivity of the iron compacts pressed at 65°C (~3.7 µΩ-m) is significantly higher than that of wrought iron (~0.1 µΩ-m). The natural oxide at the surface of the iron particles provides an insulating coating which contributes to the high electrical resistivity of these materials. This high resistivity may also be due to the presence of thin "air gaps" between iron particles created upon pressure release. A.Dawson et al. [15] studied the evolution of interparticulate bonding during the compaction of a pure iron powder using ultrasonic monitoring and showed that a good interparticle bonding exists during compaction, especially at the end of compaction, but a debonding occurs after pressure release. This suggests that during the pressure release, small "air gaps" are created between the iron particles. These gaps have a high electrical resistivity and contribute to increase the apparent resistivity of the green iron powder compacts.

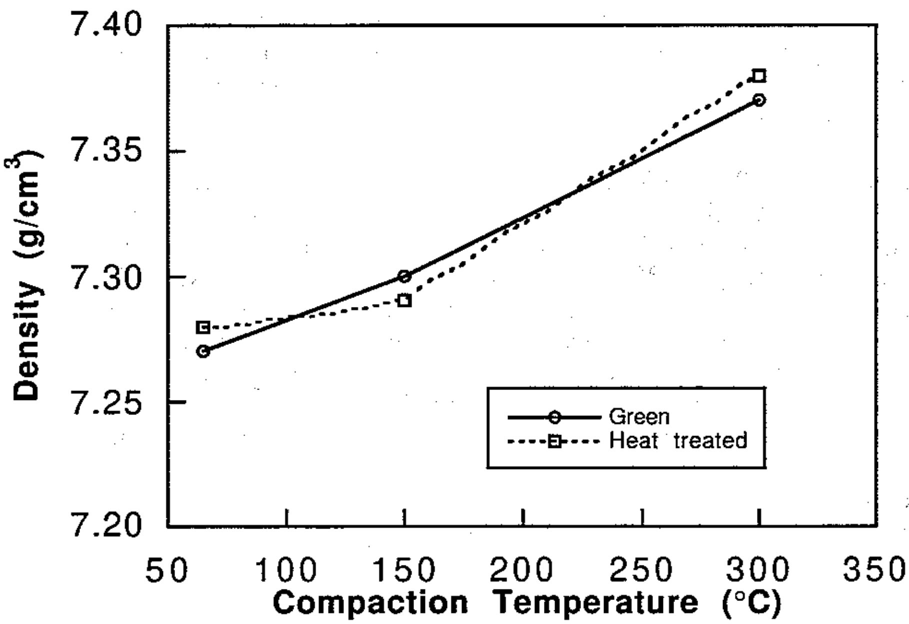


Figure 1. Effect of compaction temperature and thermal treatment (175°C/1 h in air) on the density of bars pressed at 620 MPa (45 tsi).

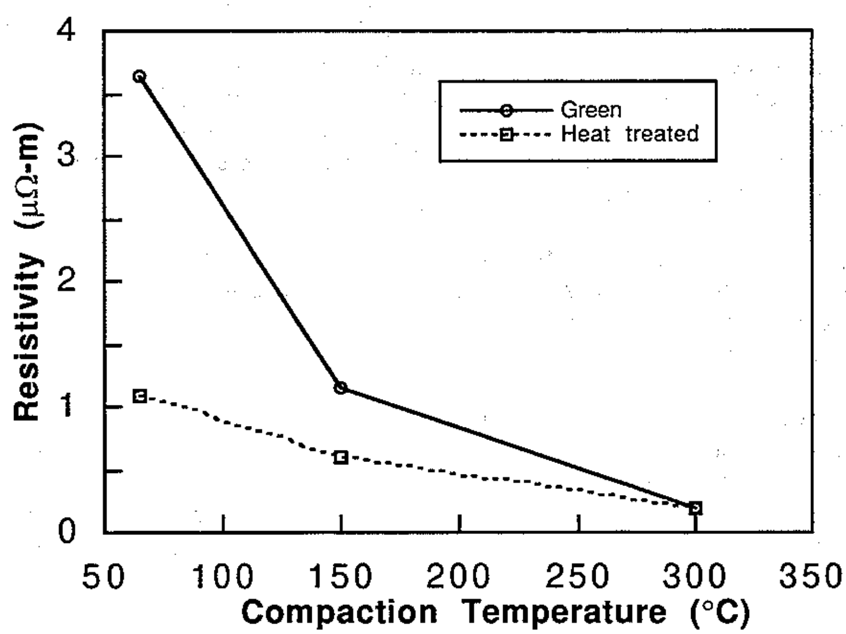


Figure 2. Effect of compaction temperature and thermal treatment (175°C/1 h in air) on the resistivity of bars pressed at 620 MPa (45 tsi).

The compaction temperature has a great impact on resistivity. It seems that during compaction, the number of electrical contacts increases as the compaction temperature increases. This can be related to an increase of the "cold welding" between iron particles when compaction temperature increases. This can also be attributed to a more effective packing of the powder and a reduction of the length of the air gap created upon pressure release when the compaction temperature increases. The heat treatment in air at 175°C for one hour also decreases the resistivity. In the case of bars pressed at 65°C for example, the resistivity drops from 3.7 μΩ-m before the heat treatment down to 1 μΩ-m after the heat treatment. The drop is associated with the formation of interparticle electrical contacts during heat treatment. The electrical contacts have been recently identified as oxide necks mainly composed of hematite (Fe_2O_3) [16]. The overall resistivity of the samples drops when these oxide necks are formed and replace the air gaps since hematite resistivity is significantly lower than air resistivity. This effect was not observed for the samples compacted at 300°C since good electrical contacts were created during compaction.

The effect of compaction temperature and a thermal treatment at 175°C in air on the transverse rupture strength of iron compacts is shown in Figure 3. The mechanical strength increases with the compaction temperature. For instance, strength increases from about 7000 psi (48 MPa) up to 18000 psi (120 MPa) for the green compacts when the compaction temperature increases from 65°C up to 300°C. This may be related to better mechanical interlocking or improved "cold welding" between the iron particles as the compaction temperature increases. The mechanical strength also increases after a low temperature thermal treatment, especially for bars pressed at low temperature. The oxide necks that form between iron particles during the heat treatment are cohesive bonds and thus, as already observed by T.Werber [17], increase the interparticle bonding. On the other hand, the effect of the heat treatment on the samples warm pressed at 300°C is not significant.

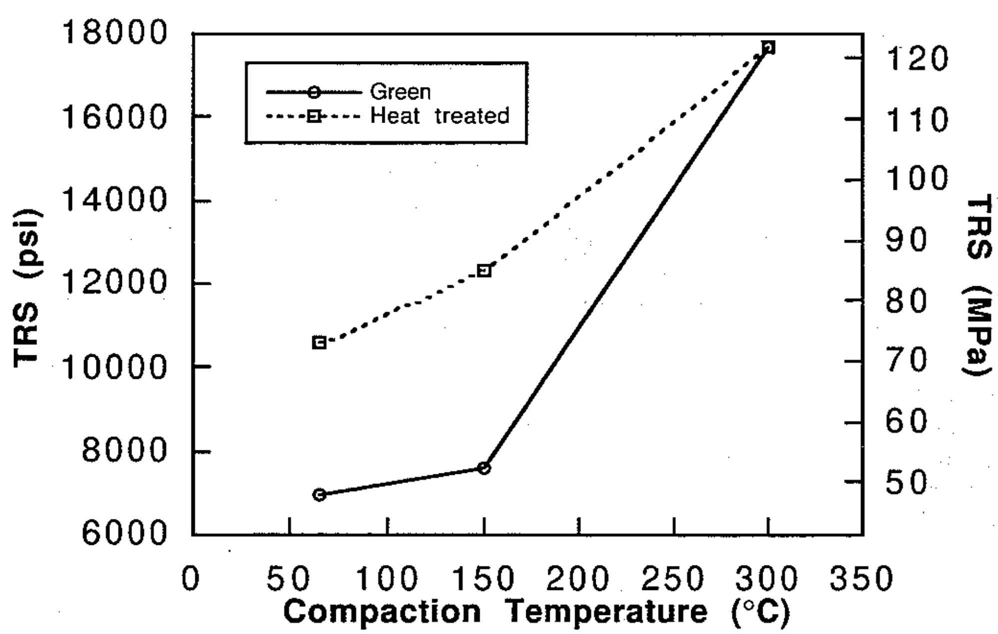


Figure 3. Effect of compaction temperature and thermal treatment (175°C/1 h in air) on the transverse rupture strength of bars pressed at 620 MPa (45 tsi).

Figure 4 shows the fracture surface of a sample pressed at 65°C/620 MPa (45 tsi) and heat treated at 175°C for 1h in air. Ductile tearing may be seen on the fracture surface suggesting that cohesive bonds were created between the iron particles. It has been verified that there are practically no dimples on the surface fracture of untreated samples pressed at 65°C/620 MPa (45 tsi). Even if the mechanical strength enhancement obtained after thermal treatment can likely not be due only to these few dimples, they give an indication that some degree of bonding occurred between the iron particles during the heat treatment.

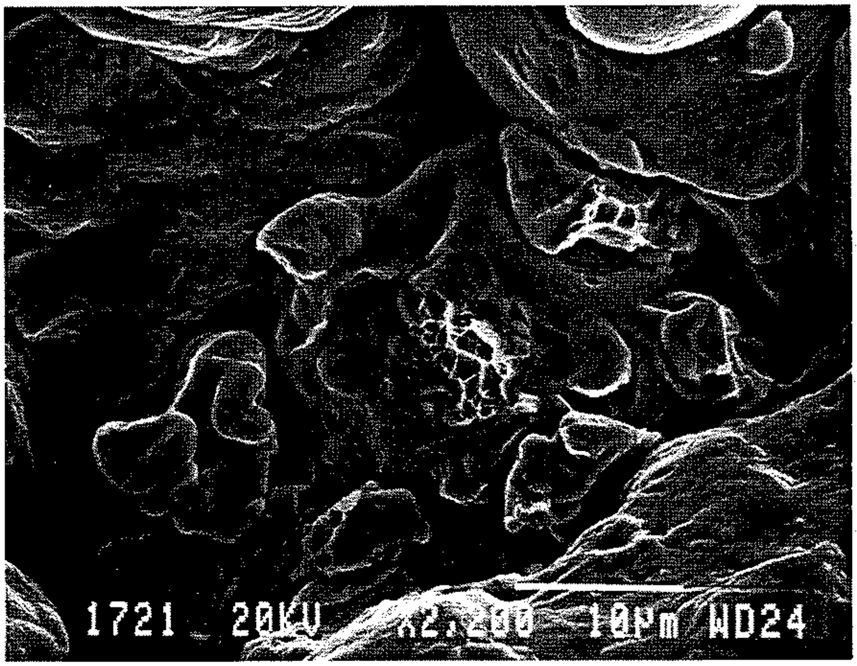
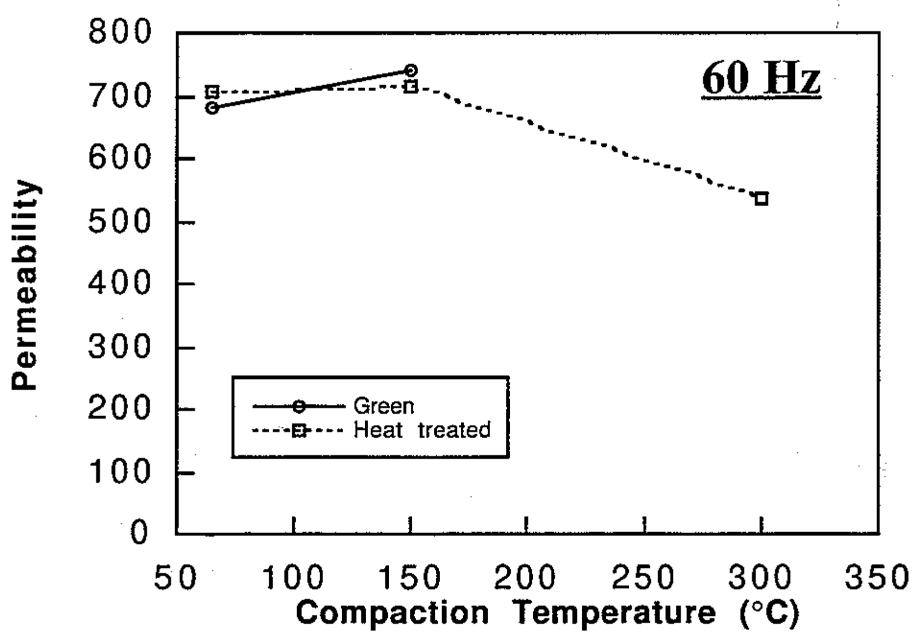


Figure 4. SEM micrograph of a fracture surface of a bar pressed at 620 MPa/65°C and heat treated at 175°C for 1 hour in air.

The effect of the compaction temperature and a thermal treatment on the AC apparent permeability at 60 and 400 Hz (0.5 T) of rings pressed at 620 MPa (45 tsi) is presented in Figure 5. The most important point to note is the high apparent permeability obtained, especially for low compacting temperature: values around 700 were obtained for the samples pressed at 65°C (which correspond to a typical temperature encountered on production presses). These permeability values are much higher than those usually obtained with iron-resin composites designed for low frequency applications fabricated under similar conditions (~450 typically). The apparent permeability decreases with an increase of the compaction temperature. This is related to the resistivity that decreases as the compaction temperature increases (see Figure 2) giving rise to eddy currents in the material. Eddy currents are opposed to the induced magnetic field and thus reduce the apparent permeability. Since eddy currents increase with frequency and conductivity (1/resistivity), this effect is more visible as the compaction temperature and the frequency increase.

Figure 6 shows the effect of the compaction temperature and a thermal treatment on the core loss of rings pressed at 620 MPa (45 tsi). The core loss increases with the compaction temperature and frequency of the magnetic field. Indeed, as the compaction temperature rises, the resistivity of the samples decreases and is no longer sufficient to keep eddy current losses at a low level. This effect is more important as the frequency increases as previously mentioned (see equation 3). However, eddy currents are not very important at 60 Hz for samples pressed at 65°C and the total core loss is low at that frequency. In fact, the resistivity of pure iron samples pressed at 65°C is significantly higher than that of wrought iron and is sufficient to keep eddy current losses low at 60 Hz.



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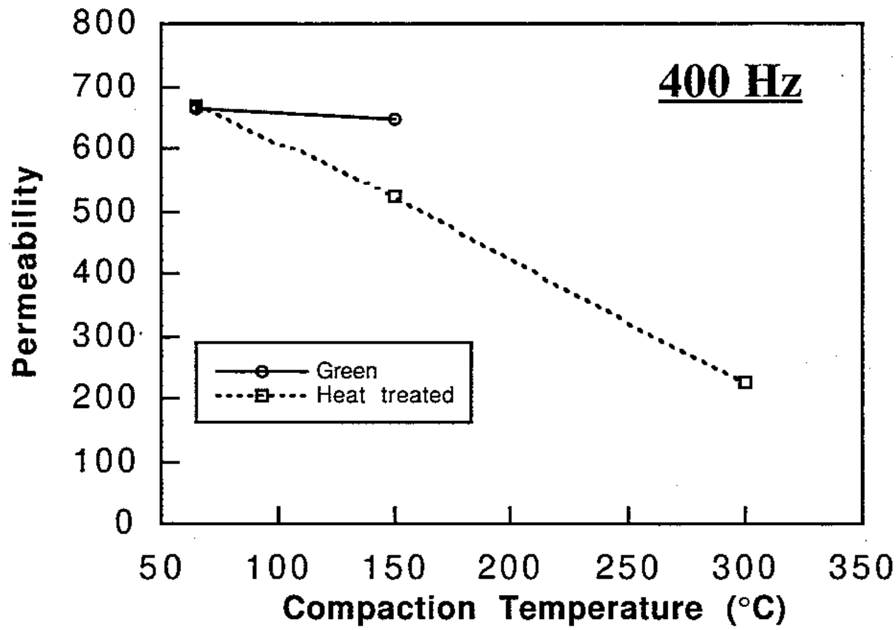
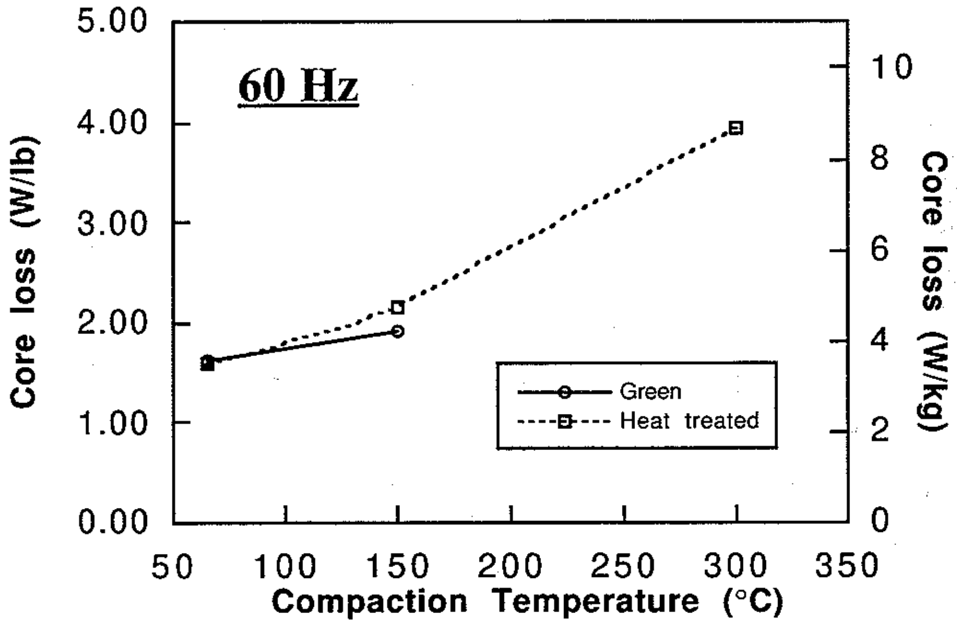


b)

Figure 5: Effect of compaction temperature and thermal treatment (1h at 175°C in air) on the permeability at 0.5T of rings compacted at 620 MPa a) 60 Hz and b) 400 Hz.



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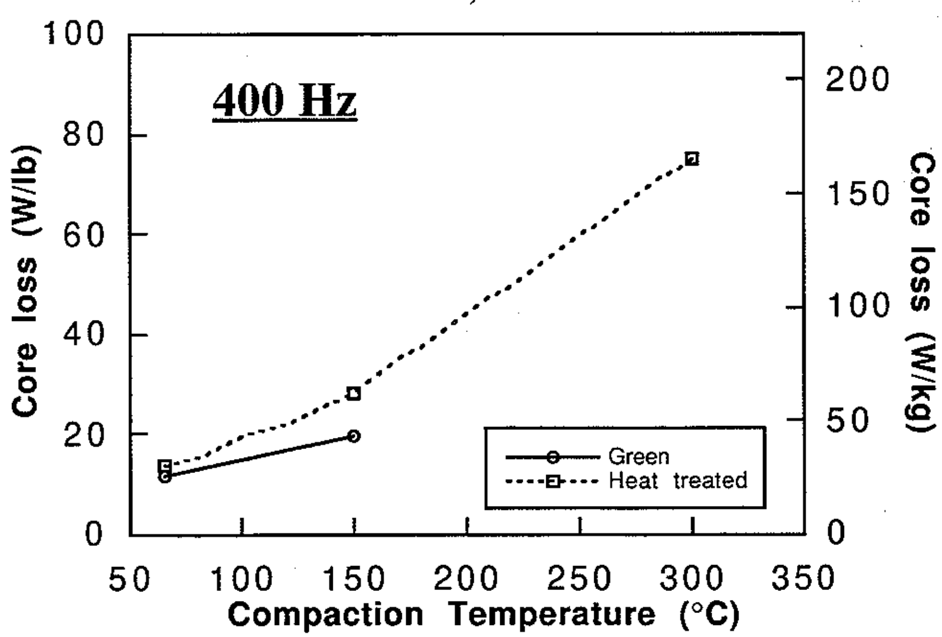

b)

Figure 6: Effect of compaction temperature and thermal treatment (1h at 175°C in air) on the core loss at 0.5T of rings compacted at 620 MPa a) 60 Hz and b) 400 Hz.

CONCLUSIONS

The effect of the compacting temperature and the effect of carrying out a low temperature heat treatment (one hour at 175°C in air) on the mechanical and AC magnetic properties has been evaluated. A material process which provides specimens with high apparent permeability while maintaining an adequate resistivity and low core loss for low frequency magnetic applications has been identified. This was achieved by using a pure iron powder. The results led to the following observations and conclusions:

- Interesting magnetic and mechanical properties were achieved by pressing at 65°C and heat treating the samples in air at 175°C for one hour.
- These parameters allowed the production of material with mechanical strength of 73 MPa (~ 10500 psi), an AC apparent permeability of 700 and a core loss of 3.5 W/kg (at 0.5 T and 60 Hz).
- An increase in the compaction temperature decreased the electrical resistivity which rose eddy currents and consequently increased the core loss.

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