

# The role of processing conditions on the magnetic properties of insulated iron powder compounds at low frequencies

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The main aim of the paper are analysis the effect of the processing conditions on the magnetic behaviour of iron insulated powder compound (IIPC) materials admixed by aluminium alloy at low frequencies. Results show that the higher applied compactive pressures cause a greater reduction of volumes and of present porosities. The behaviour of powders during the pressing process and heat treatment is important question in the improving of IIPC materials to give a suitable combination between pressing pressure, sintering temperature and time as well as magnetic properties. The coercivity and the remanence increased with increasing applied pressure that is also attributed to the enhanced densification and promote porosity reduction. However, the subsequent decrease of remanence and increase of coercivity are observed in terms of addition of aluminium alloys.

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## 1. Introduction

The powder metallurgy (PM) is a technology for the large-scale manufacturing of net shape parts. The profitable PM manufacturing route for structural parts manufacture consists of compaction and sintering stages and gives high productivity with low energy consumption and high material utilization and can significantly modify the way of projecting several devices or parts regarding magnetic circuits [1, 2].

The interest in soft magnetic applications for ferrous PM components during the last several years are increased, due to the fact that these materials exhibit many unique and interesting physical and chemical properties with a number of potential technological applications [3-14].

For parts with complicated shapes, final machining operations are frequently necessary. This can have particular significance for soft magnetic materials (SMM), since the mechanical work applied to the part will produce dislocations and stress fields at the part surface, with the depth of penetration depending upon the severity of the machining operation. This deformation will increase the coercive force and remanence and raise the level of hysteresis losses. It is therefore necessary to anneal the component after machining in order to relax internal stresses and remove dislocations. Annealing must be carried out under protective atmosphere, with a very slow cooling rate [12].

Representing one of SMM, insulated iron powder compacts are basically pure iron powder particles coated with a very thin electrically insulated layer. Some of the

driving forces for conversion from laminated steel sheets to PM components for soft magnetic applications that were listed included: freedom of design, with the possibility of more complex design, coupled with lower core losses than for laminated steel at higher AC frequencies, providing overall cost savings [11, 13]. SMM are ideally suited to the production of the complex shaped stators and rotors used in, mainly, automotive industry and application in many other fields, such as the computing industry, household appliances, or measuring equipment [11].

Magnetic properties of the IIPC are influenced by the amount and type of polymer and the particle size distribution of the iron powder. They are basically used in the as compacted condition (a heat treatment at low temperature is eventually applied but with no sintering between the particles) and exhibit low eddy current losses. Applications for these materials are AC magnetic devices that require the minimization of eddy current losses. One drawback of the iron powder polymer composites is the high coercive force of the as pressed component. This high coercive force increases the hysteresis losses dramatically, resulting in reduced magnetic performance at low frequencies (less than 200 Hz). Consequently, these materials have found usage in higher frequency applications but are not well suited for the low frequency, high volume applications at 60 Hz [3, 12, 13].

Therefore, the main aim of the presenting paper is to find proper electromagnetic properties usage in low frequency applications at 50 Hz, considering the trend towards a more widespread use of automotive electric systems in motors, considering that density, precision and geometry complexity are required.

Consequently, by means of aluminium alloy additives to the IIPC is to find possibility achieved lower iron losses with respect of density/porosity developments in studied materials as well as suitable magnetic performance in terms of remanence and coercivity.

## 2. Experimental materials and methods

The starting materials were IIPC powder and aluminium alloy. Chemical composition of aluminium alloy is given in the Table I.

Table 1. Chemical composition of aluminium alloy in wt. %

Al	Cu	Mg	Zn	Wax
Bal.	1,6	2,5	5,5	1,0

The processing conditions are presented in Fig. 1.

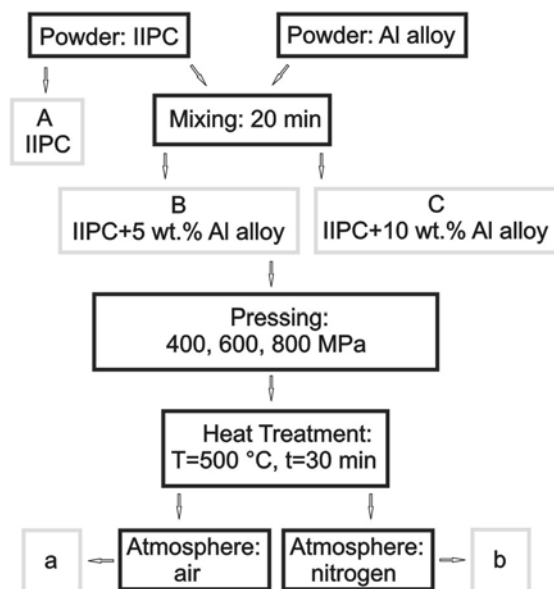


Fig. 1 Processing conditions of investigated materials

Powder mixtures were homogenized using a laboratory Turbula mixer for 20 min. Specimens with a different green density obtained using a 2000 kN hydraulic press, in a disc-shaped mould ( $\phi$  40 mm) and unnotched impact energy  $55 \times 10 \times 10 \text{ mm}^3$  specimens applying a pressing pressure of 400, 600 and 800 MPa. Different thermal treatments (in air and in nitrogen) were carried out on the evaluated systems, all implying a step at the maximum temperature of 500 °C for 30 min. Densities were evaluated using the water displacement method.

Magnetic tests system realization and samples characterization has been equipped with two windings: the first one to produce magnetization in the core with

appropriate m.m.f., the second one to pick up the magnetic induction.

The microstructural characterization was carried out on unetched specimens using an optical microscope LEICA MPEF4 equipped with an image analyzer and SEM JEOL 7000F. The metallographic specimens were impregnated with resin under vacuum in order to avoid any pore distortion during polishing.

## 3. Results and discussion

In the microstructure in both processing condition along with microstructure of material in as-pressing state are presented in Fig. 2-4.

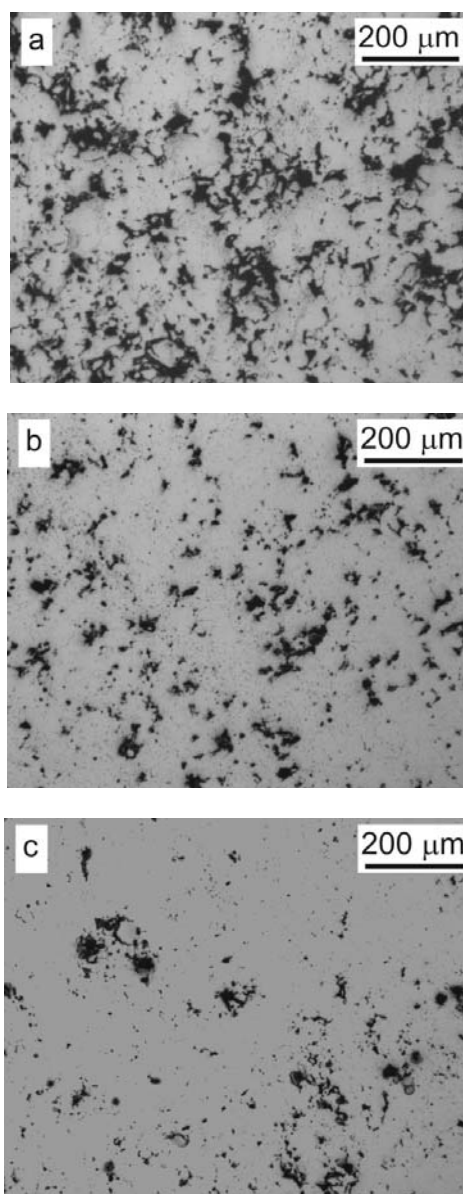
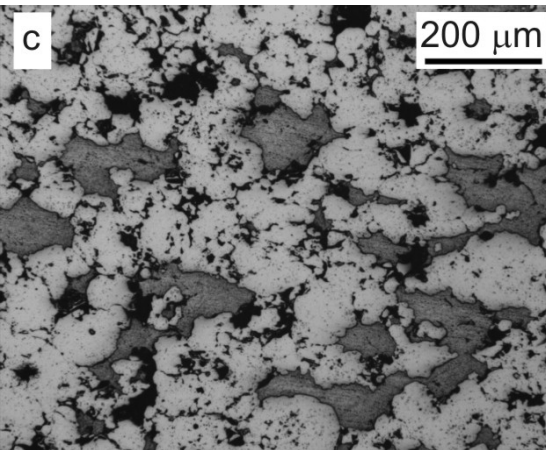
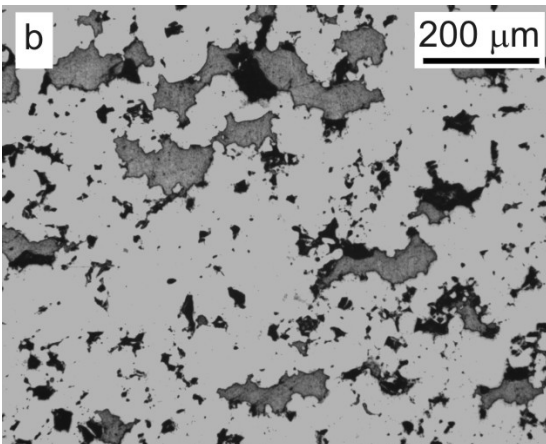
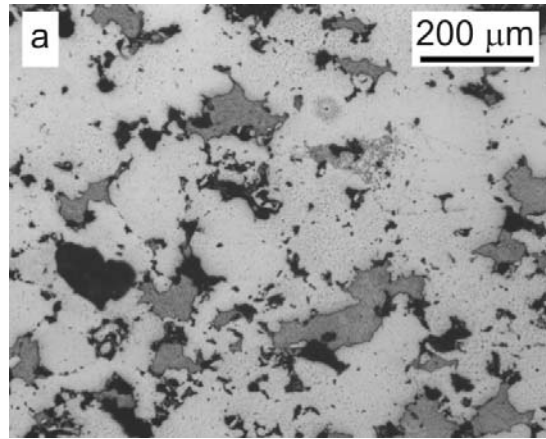
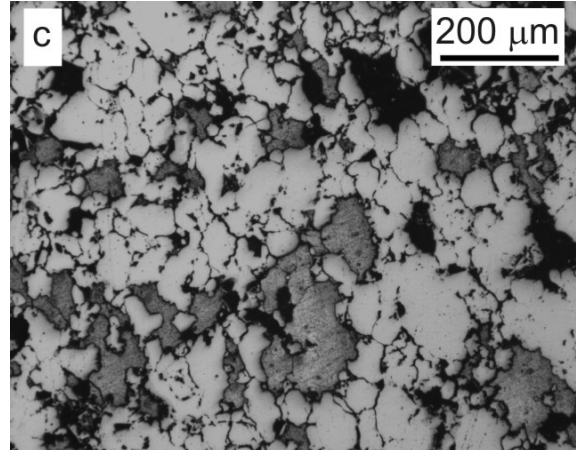
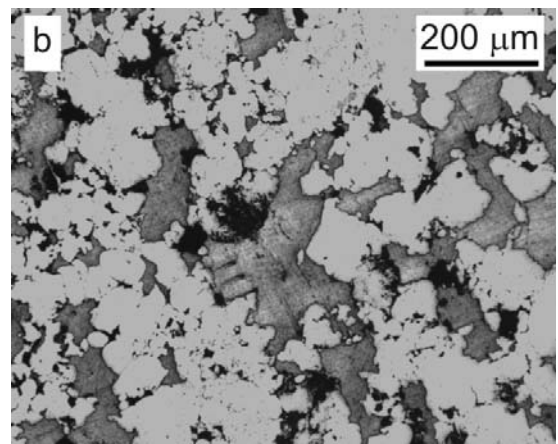
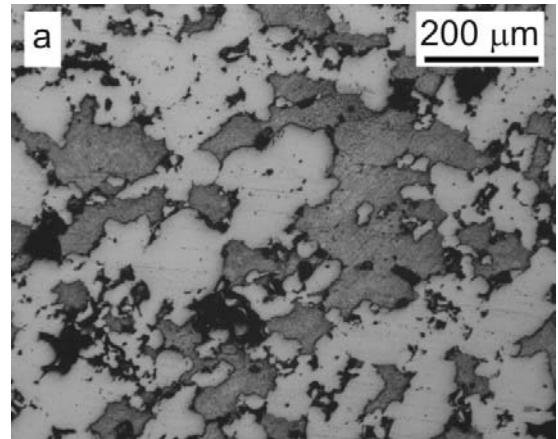


Fig. 2 Microstructure of investigated material A at processing conditions: a - pressing pressure of 400 MPa, b - 400 MPa + Heat Treatment in air, c - 400 MPa + Heat Treatment in nitrogen.



*Fig. 3 Microstructure of investigated material B at processing conditions: a - pressing pressure of 400 MPa, b - 400 MPa + Heat Treatment in air, c - 400 MPa + Heat Treatment in nitrogen*



*Fig. 4 Microstructure of investigated material C at processing conditions: a - pressing pressure of 400 MPa, b - 400 MPa + Heat Treatment in air, c - 400 MPa + Heat Treatment in nitrogen*

It is clearly presented that with increase aluminium alloy content in iron matrix increase the distribution and volume of aluminium particles. Heat treatment results in a coarse-grained structure with a minimum number of inclusions within the grains and at the grain boundaries. Sintering of aluminium has proven to be more effective when carried out in full nitrogen atmospheres according to the [15, 16]. This result is confirmed by the analysis of microstructures of treated samples (as shown in previous pictures), even if the heat treatment is carried out at temperature lower than the average sintering temperature of aluminium alloys. Since even small quantities of impurities can severely degrade magnetic properties, high-purity atmospheres are required to maintain impurities such as C, O, and N levels very low, therefore using nitrogen atmosphere promoting a better distribution of aluminium particles, and consequently porosity distribution at the prior particle boundaries. The microstructures investigation in materials with aluminium alloy contents (B and C systems) reveals that the pores are oriented near or surrounding the aluminium particles. Annealing supplement to diffusion and stress relaxation, therefore, reduce their size. The morphology and distribution of porosity in PM aluminium alloys are presented in [17-20].

The magnetic properties of investigated materials are presented in the Table 2 and Table 3.

Table 2. Magnetic properties of investigated material in air.

No.	Density [kg·m <sup>-3</sup> ]	Iron Loss [W/kg]	Remanence [T]	Coercivity [A/m]
Aa	6,97	11,3	0,021	184
	7,39	8,3	0,027	205
	7,47	9,85	0,023	218
Ba	6,36	15,6	0,007	196
	6,52	14,8	0,012	220
	6,66	25,3	0,023	312
Ca	5,77	50	0,005	227
	5,85	54,5	0,006	310
	5,9	34,2	0,01	331

It is well-known that porosity has a negative effect on the magnetic properties such as the magnetic induction and the coercive force, which their influence are decreasing and increasing, respectively. Comparison of the results indicates that the magnetic properties are considerably dependent on the structural state of the alloy. In PM areas the relationship between the density or porosity and the applied pressure is a classical way for the evaluation of the powder compressibility (powder properties during pressing). Therefore, porosity is a reciprocal value to the density. Hence, the relationship between the density and the iron losses are plotted in Fig. 5.

Table 3. Magnetic properties of investigated material in N<sub>2</sub>

No.	Density [kg·m <sup>-3</sup> ]	Iron Loss [W/kg]	Remanence [T]	Coercivity [A/m]
Ab	6,99	9,85	0,024	164
	7,41	8,7	0,02	230
	7,51	7,8	0,032	234
Bb	6,36	15,2	0,007	165
	6,71	12,5	0,014	209
	6,87	14	0,015	265
Cb	5,69	29,4	0,005	182
	5,94	26,4	0,006	267
	6,02	33,8	0,01	312

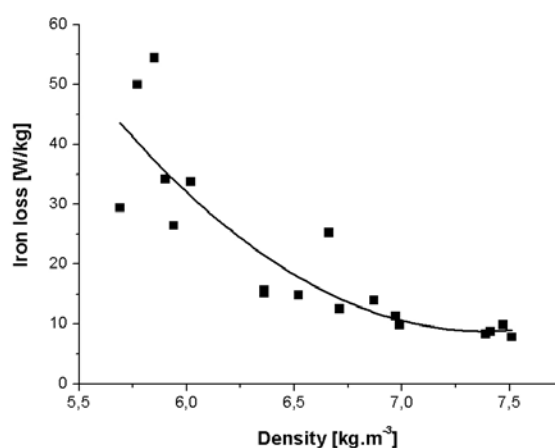


Fig. 5 Density curves in relationship with iron loss results of investigated materials.

The results show that higher value of density can be contributed to the lower value of iron loss. It can be seen, that the magnetic properties of the specimens noticeably change due to the density developments. During the pressing pressure, plastic deformation of the particles takes place that results in higher iron losses (mainly hysteresis losses). Therefore, the knowledge of compaction processes needs to be explored. The aim would be to reduce as much as possible the hardening effects of iron powders in order to minimize the iron losses.

Various authors [8, 10-14] emphasizes that the behaviour of powders during the pressing process and heat treatment is important question in the improving of IIPC materials to give a suitable combination between pressing pressure, heat treating regime as well as magnetic properties.

The typical B-H magnetization behaviour for investigated materials in both processing conditions is presented Figs. 6-8.

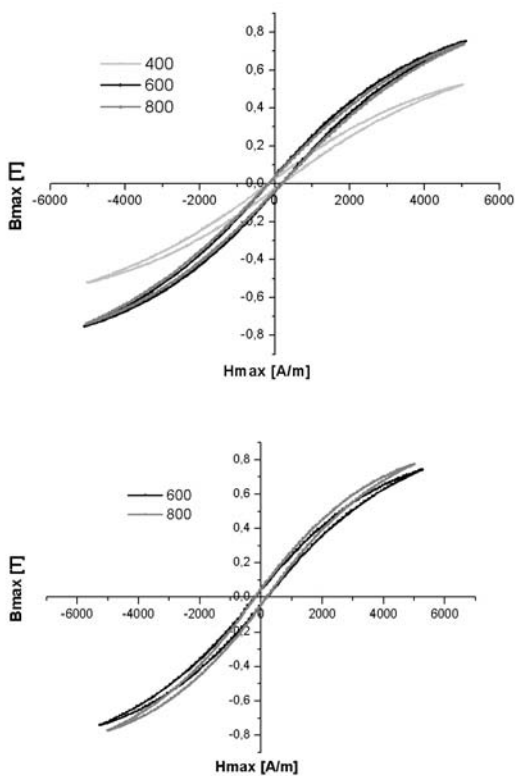


Fig. 6 B-H curves of investigated material A at 50 Hz treated in: a - air and b - nitrogen

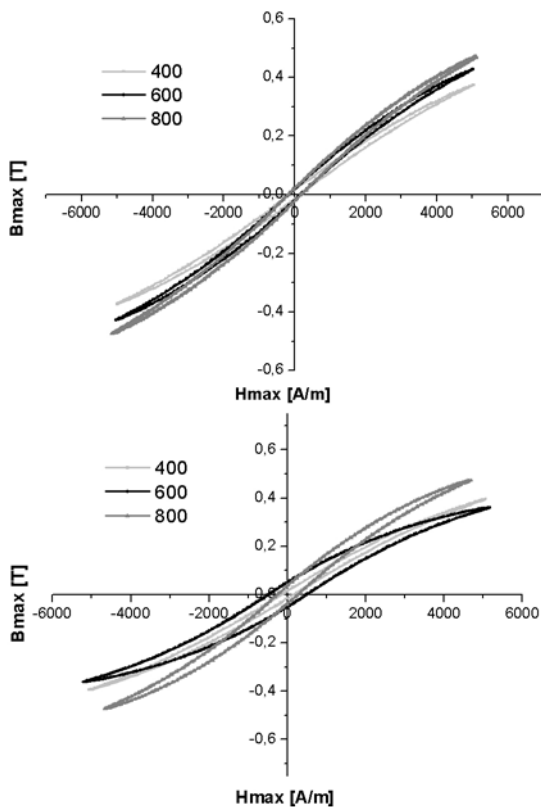


Fig. 7 B-H curves of investigated material B at 50 Hz treated in: a - air and b - nitrogen

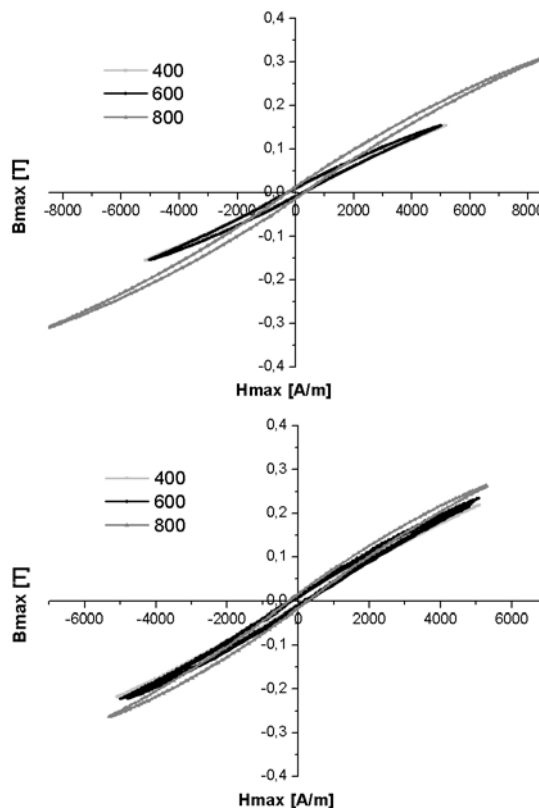


Fig. 8 B-H curves of investigated material C at 50 Hz treated in: a - air and b - nitrogen

Residual porosity has a negative effect on the magnetic properties of investigated materials, substantially decreasing the remanence and increasing the coercivity. Therefore, with increasing density the magnetic properties of tested materials increased. In terms of aluminium alloy addition, the subsequent decrease of remanence and increase of coercivity are observed. The maximum values of coercivity (about 300 A/m) were attained mainly in case of both higher aluminium additives and compactive pressures.

These insulated materials have several advantages over a traditional comparable to laminated sheets, mainly in electrical motors.

The magnetic properties of the IIPC are isotropic (materials have the same properties in all directions). Therefore, materials are a low-cost produced as smooth net shape forms, freedom of design complex shapes and good surface finish. Stable dimensions after processing allow very tight tolerances as well as segments can be combined to create larger, isotropically integral structures [7, 10, 12, 21, 22]. This allows for tighter more efficient windings, which in turn give a higher thermal conductivity, and permit a higher current input. This also allows a reduction in the amount of copper required, which can give an improvement in the performance of a motor.

#### 4. Conclusions

The obtained results can be summarized as follows:

The coercivity and the remanence increased with increasing applied pressure that is also attributed to the enhanced densification and promote porosity reduction.

In terms of addition of aluminium alloys, the subsequent decrease of remanence and increase of coercivity are observed.

The behaviour of powders during the pressing process and heat treatment is important question in the improving of IPC materials to find an appropriate combination between processing conditions and magnetic properties.

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