

The role of chemical composition and processing conditions on soft magnetic materials behaviour

R. BIDULSKÝ, M. ACTIS GRANDE, L. FERRARIS, J. BIDULSKÁ^a

Politecnico di Torino-Alessandria Campus, Viale T. Michel 5, 15100 Alessandria, Italy

^a*Faculty of Metallurgy, Technical University of Košice, Letná 9, 042 00 Slovakia*

The present paper focused on the analysis of the fracture surfaces and magnetic properties of a new development Insulated Iron Powder Compound (IIPC) with addition of the aluminium alloy in order to investigate bonding evolution in investigated materials. Results show that in the pressed state, mainly pores act as crack initiators and due to their presence the distribution of stress is inhomogeneous across the cross section and leads to the reduction of the effective load bearing area. Heat treatment supplement to diffusion and stress relaxation, therefore, reduce their size. The lower values of impact energy are confirmed by brittle fracture observed through fracture surfaces for both processing conditions. Investigation of fracture surfaces concluded that improvements in bonding during the pressing process and heat treatment can be helpful in the development of Soft Magnetic Composite (SMC) to give a suitable combination between pressing pressure, annealing temperature and time as well as magnetic properties.

(Received May 28, 2010; accepted June 16, 2010)

Keywords: soft magnetic material, aluminium alloy, fracture surface

1. Introduction

The powder metallurgy, and in particular the possibility to manufacture net shape parts, can significantly modify the way of projecting several devices or parts regarding magnetic circuits. One of the electromagnetic applications is powder core, which use iron powder dispersed in a plastic or polymer compacted to different shapes [1-4]. These cores provide a constant permeability over wide range of frequencies. Iron powder cores are the lowest cost alternatives to ferrites but can provide a higher induction compared to soft ferrites. The applications include switch mode power supplies, inductors and other high frequency broadband applications [3].

The soft magnetic composite (SMC) materials are possible divided to [1-12]: iron powder (basic element for the preparation of low alloyed powder mix), iron-nickel alloy powder, iron-phosphorus alloy powder, iron-cobalt alloy powder, Insulated Iron Powder Compounds (IIPC.).

Representing one of SMC materials, insulated iron powder compacts are basically pure iron powder particles coated with a very thin electrically insulated layer. In this case the components made of metal powder cannot be sintered, as it is fundamental that each particle is electrically insulated from the other. Nevertheless, since during compaction a stress is introduced in the particles, which deteriorates the soft magnetic properties, a heat treatment has to be settled to provide a stress relief. [3].

The effect of the processing parameters on the magnetic properties achievable by SMC has already been evaluated elsewhere [1-6]. It was concluded that improvements in bonding during the pressing process and heat treatment can be helpful in the development of SMC

materials to give a suitable combination between pressing pressure, annealing temperature and time as well as magnetic properties.

Tajima et. al [13] stated that the SMC materials are rarely used for motors because both their magnetic flux and their strength are weak. The reports about the strength properties with respect to magnetic properties are still few in literature survey [13-15]. Therefore the strength with adequate magnetic properties in terms of bonding evolution between powder particles is the main aim of the present work. Additionally, the analysis of the chemical composition and processing conditions of an IIPC with addition of the aluminium alloy were studied.

2. Experimental materials and methods

The starting material was I.I.P.C. with an addition of 5% aluminium alloy. Chemical composition of aluminium alloy is given in the Table 1.

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

Al	Cu	Mg	Zn	Wax
Bal.	1.6	2.5	5.5	1.0

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 (ϕ 40 mm) and unnotched impact energy $55 \times 10 \times 10 \text{ mm}^3$ specimens applying a pressure in the range from 400 to 800 MPa. Heat treatment was carried out in vacuum furnace at 500°C for 30 min

(annealing). Densities were evaluated using the water displacement method.

Different types of tests can be adopted for the characterization of the mechanical properties of powder metallurgy products, among which tensile and bending tests. In particular bending tests are preferred to evaluate strength of low ductility or brittle sintered materials, such as highly porous sintered materials, metal-non metal composite materials, ceramics and “green” samples. This is due to the fact that the amount of deformation during bending is greater than under tensile load. The plastic objective is determination of the impact energy of unnotched PM test specimens according the MPIF Standard Test Methods and Standard 40. The test is based on the measurement of energy absorbed when a test piece is fractured by the application of an impact force.

3. Results and discussion

The production of components via standard press and sinter PM techniques requires the use of lubricants to reduce the friction between the metal powders and die walls during compaction and ejection, as well to minimize tool wear. Die-wall lubrication allows the fabrication of PM parts having high density and good green and sintered properties [16, 17]. For this reason, there is still an interest in press ready mixes that can be shaped easily due to the press-ready aluminium powder was added to the presented mixture. In order to investigate the bonding evolution in investigated materials, specimens after both processing condition: pressing and annealing were analysed. The density tendency of studied systems was shown in the Fig. 1.

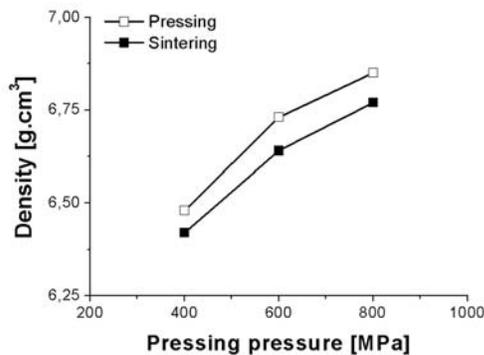


Fig. 1 The density development in studied materials.

According to presented graph in Fig. 1, the annealing influences the density that is lower than for the pressing systems. This is well-known problem connected to PM aluminium alloys sintering as well as sintering processing associated with wetting behaviour, swelling/shrinkage and particle size distribution during heat treatment, mainly connected to vacuum atmosphere [18-21]. Solid state sintering of Al base compacts has so far been unsuccessful

due to the stable oxide layers on each particle. Since Al sintering is sensitive to the presence of oxygen, the lubricant should also burn out in a non-oxidizing atmosphere.

On the other hand, the results show an improved tendency of specimens underwent by plastic deformation than for specimens underwent only by pressing. This assumption was confirmed by results from mechanical tests, mainly by value of impact energy that as seen from Figs. 2 and 3.

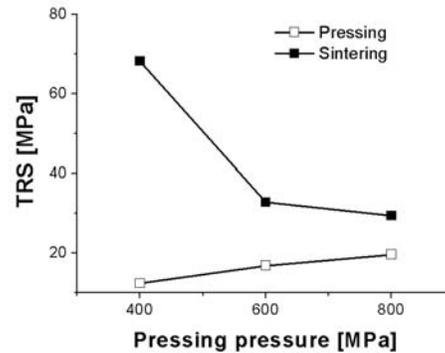


Fig. 2 Transverse Rupture Strengths of investigated materials with respect to applied pressing pressure

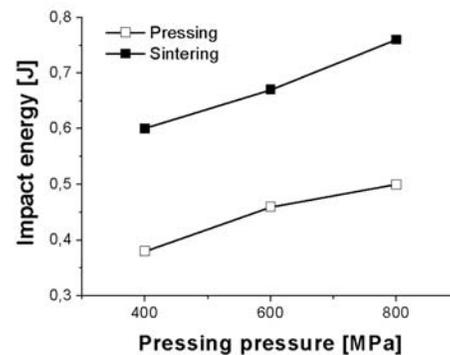


Fig. 3 Plastic properties of investigated materials.

In term of mechanical properties, the lower pressing pressure together with sintering shows value of bending strength near the 70 MPa. Application of higher pressing pressure together with sintering leads to markedly decreases up to the value of bending strength near the 30 MPa. In the pressed state, mainly pores act as crack initiators and due to their presence the distribution of stress is inhomogeneous across the cross section and leads to the reduction of the effective load bearing area. Annealing supplement to diffusion and stress relaxation, therefore, reduce their size. Such a contrary behaviour in sintering state is still without a clear explanation and needs a deeper investigation. The typical fracture surfaces for investigated materials are presented in Figs. 4-8.

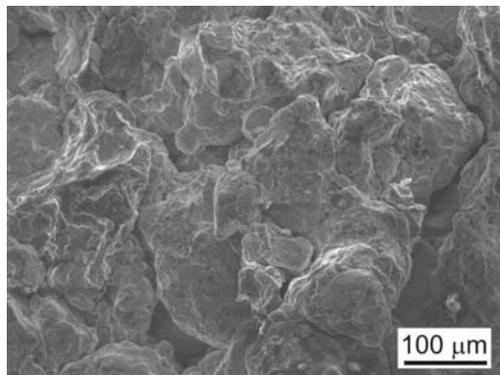


Fig. 4. Fracture surface of specimens after pressing at 400 MPa.

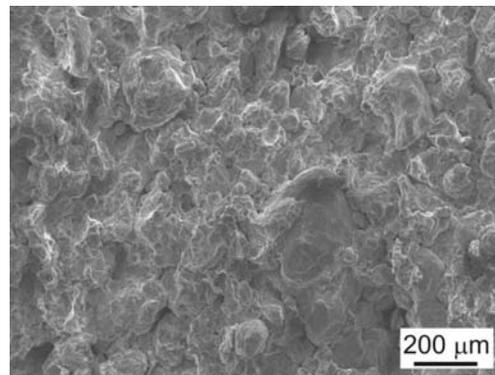


Fig. 7 Fracture surface of specimens after pressing at 600 MPa and annealing at 500°C / 30 min.

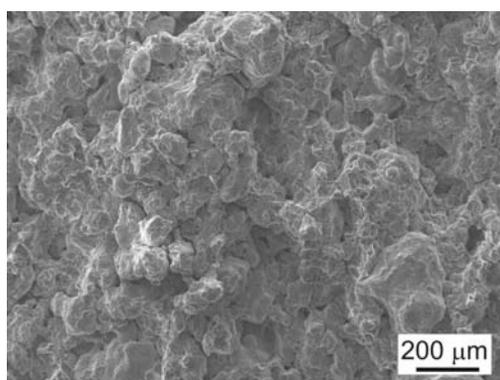


Fig. 5 Fracture surface of specimens after pressing at 400 MPa and annealing at 500°C / 30 min

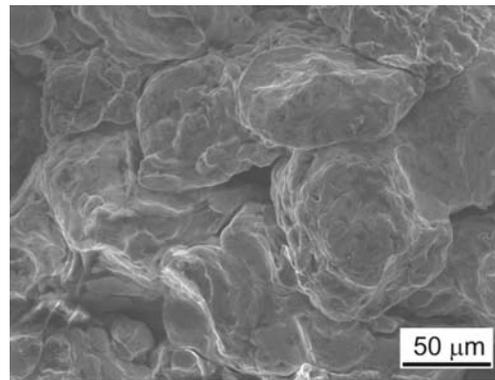


Fig. 8 Fracture surface of specimens after pressing at 800 MPa.

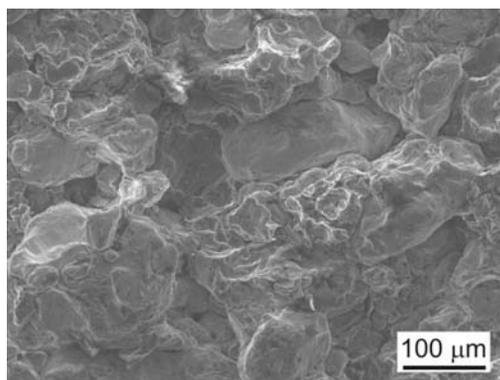


Fig. 6 Fracture surface of specimens after pressing at 600 MPa

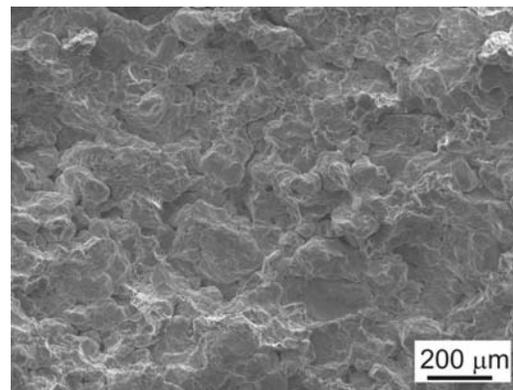


Fig. 9 Fracture surface of specimens after pressing at 800 MPa and annealing at 500°C / 30 min.

The lower values of impact energy are confirmed by brittle fracture observed through fracture surfaces for both processing conditions. It is evident that fragmentation of the primary particles occurs.

It is considered that the broken particles can then fall into smaller spaces owing to their reduced sizes, and thus bring about a volume reduction. Size reduction by brittle fracture cannot continue indefinitely, and, ultimately, a transition to compaction by plastic deformation will occur as the pressure increases [22]. Compaction by brittle fracture is accompanied by an increase in the surface area of the compact with fragmentation of brittle porous aggregates of primary particles.

It is clear from magnetization properties at 50Hz supply frequency given in Table 2 that the magnetic properties of the specimens noticeably change due to the density developments.

Table 2. Magnetic properties of investigated material.

Pressure	Density	Specific Losses	Br	Hc
[MPa]	[kg/m ³].10 ⁻⁶	[W/Kg]	[T]	[A/m]
400	6.42	17.93	0.011	289
600	6.64	18.19	0.007	280
800	6.77	27.48	0.019	422

The remanence (Br) and the coercivity (Hc) increased with increasing density that is also attributed to the enhanced densification. However, the subsequent decrease of remanence and increase of coercivity are observed in terms of addition of aluminium alloys. The maximum values of coercivity (about 400 A/m) were attained mainly in case of higher compactive pressures; i. e. as consequence of the higher applied forces that cause a greater reduction of volumes and of present porosities, which typically results in a demagnetization field effect.

It has been found that presented results with addition of aluminium alloy, in terms of noticeably plastic and strength properties obtained, seem to be suitable materials for the electromagnetic applications.

4. Conclusions

The obtained results can be summarized as follows:

1. In term of mechanical properties, the application of 400 MPa pressing pressure together with heat treatment condition (500°C for 30 min) shows value of bending strength near the 70 MPa. The lower values of impact energy are confirmed by brittle fracture observed through fracture surfaces for both processing conditions.

2. The behaviour of powders during the pressing process and heat treatment is important question in the improving of SMC materials to give a suitable combination between pressing pressure, sintering temperature and time as well as magnetic properties.

3. Some additional considerations should be necessary also for what it concerns the working permeability.

References

- [1] D. Hadfield, Powder Metall. **25**, 136 (1982).
- [2] P. Jansson, Powder Metall. **35**, 63 (1992).
- [3] M. Actis Grande, A. Boglietti, A. Cavagnino, L. Ferraris, P. Ferraris, IECON 2009, IEEE Industrial Electronics Society, 1130 (2009).
- [4] L. Hultman, O. Andersson, A. Jack, SAE Transactions **112**, 158 (2003).
- [5] I. Glibert, S. Bull, T. Evans, A. Jack, D. Stephenson, A. de Sa., J. Mater. Sci. **39**, 457 (2004).
- [6] L.A. Dobrzanski, M. Drak, B. Ziebowicz, J. Mater. Process. Technol. **191**, 352 (2007).
- [7] Y. G. Guo, J. G. Zhu, D. G. Dorrell, IEEE Trans. Magn. **45**, 4582 (2009).
- [8] A. H. Taghvaei, H. Shokrollahi, K. Janghorban, J. Magn. Mater. **321**, 3926 (2009).
- [9] J. Fuzer, P. Kollar, J. Fuzerova, S. Roth, IEEE Trans. Magn. **46**, 471 (2010).
- [10] E. Enescu, P. Lungu, S. Marinescu, P. Dragoi, J. Optoelectron. Adv. Mater. **8**, 745 (2006).
- [11] I. Chicinas, O. Geoffroy, O. Isnard, V. Pop, J. Magn. Mater. **290**, 1531 (2005).
- [12] L. Anestiev, M. De Wulf, L. Froyen, L. Dupre, J. Melkebeek, J. Magn. Mater. **281**, 124 (2004).
- [13] S. Tajima, T. Hattori, M. Kondoh, H. Kishimoto, M. Sugiyama, T. Kikko, IEEE Trans. Magn. **41**, (2005).
- [14] N. Takahashi, T. Imahashi, M. Nakano, D. Miyagi, T. Arakawa, H. Nakai, S. Tajima IEEE Trans. Magn. **43**, 2749 (2007).
- [15] I. Hemmati, H.R.M. Hosseini, S. Miraghaei, Powder Metall. **50**, 86 (2007).
- [16] R. Bidulský, M. Actis Grande, M. Kabátová, M. Selecká, Acta Metallurgica Slovaca **14**, 349 (2008).
- [17] E. Hryha, E. Dudrova, S. Bengtsson, Powder Metall. **51**, 340 (2008).
- [18] G. B. Schaffer, T. B. Sercombe, R. N. Lumley Mater. Chem. Phys. **67**, 85 (2001).
- [19] J. M. Martín, B. Navarcorena, I. Arribas, T. Gómez-Acebo, F. Castro, Euro Powder Metallurgy 2004, Wien, Shrewsbury, EPMA; **4**, 46 (2004).
- [20] H. Danninger, H.C. Neubing J. Gradl, Powder Metallurgy'98, Granada, Shrewsbury, EPMA; **5**, 272 (1998).
- [21] J. Bidulská, R. Kočíško, R. Bidulský, M. Actis Grande, Acta Metallurgica Slovaca **16**, 4 (2010).
- [21] P.J. Denny, Powder Technol. **127**, 162 (2002).

*Corresponding author: robert.bidulsky@polito.it