Research Article

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Innovative Soft Magnetic Composite Materials: Evaluation of magnetic and mechanical properties

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Abstract: Electrical machines cover a very wide range of applications in many industrials sectors and the research to improve the performance of those applications is recently leading to the development of new solutions. Those devices are generally equipped with magnetic circuits made of laminated ferromagnetic steel, but in the last decade, new magnetic materials have been developed to realise magnetic circuits: Soft Magnetic Composites (SMC). The Authors have investigated SMCs with organic layer obtained through the adoption of phenolic and epoxy resins; in previous research activities several mixture compositions have been produced and analysed with different percentages of binder and compacting pressures. Promising results regarding magnetic and mechanical performances have been obtained using a very low binder content. The paper aims to investigate the lower limit of the binder to be used, still keeping good mechanical properties. Appropriate magnetic tests have been performed on toroidal specimens: good magnetic characteristics have been obtained, maintaining on the other side proper mechanical strength.

Keywords: Soft Magnetic Composites (SMC), powder metallurgy (PM), magnetic characterisation, mechanical properties, epoxy resin, phenolic resin

1 Introduction

The growing demand for higher efficiencies in several industrial sectors focuses the research to find new solutions in many application fields. The electrical machines represent a predominant part of such applications, and the use of new magnetic materials improving the performances [1] and leading to a better power/weight ratio is a proposed investigation. The idea to propose new materials in substitution of traditional ones applies to:

– NdFeB bonded magnets are generally used replacing ferrites [2], and in some case, even NdFeB sintered magnets [3];
– SMC (Soft Magnetic Composites) may replace laminated steels [4–7].

In the recent past, the Authors studied and examined the aforementioned typologies of magnetic materials [2, 8–10]. Different tests and prototypes [11] have been realised obtaining promising results for both magnetic and mechanical properties [10].

The present work is focused on SMC materials: pure iron grains are coated and insulated with a layer, which can be of organic or inorganic nature. The advantages of such materials with respect to traditional laminated steel lie in different features: the capability to lead the magnetic flux in all directions, the reduction of the volumes, the possibility to produce components in new complex geometries, and the lowering of iron losses, mainly with the reduction of eddy currents, at medium and high frequency. Furthermore, the adoption of magnetic powder moulding may lead to a strong simplification of the production process: if the desired geometry presents a difficult construction with magnetic sheets, the use of moulded parts can represent a satisfactory solution. New typologies of electrical motors may be designed and produced with the adoption of SMC materials [12]: for instance Axial Flux Motors (AFM) [14–16], Transverse flux motors (TFM) [17, 18] and Claw pole motors [19].

The research carried out in the Alessandria site of Politecnico di Torino with the support of the polymeric and metallurgic research groups, investigated the phenolic and epoxy resins as a new particular layer to produce the innovative SMC materials [9, 10]. The main goal of this work is to evaluate the magnetic, and mechanical properties of SMC obtained using a very low content of polymeric binder. In previous activities, fractional contents in the weight of phenolic and epoxy resins had been adopted.

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The obtained results suggested that the binder content can be further optimised; the attention has therefore been focused on investigating the magnetic and mechanical properties, further reducing the percentage of the polymer in the mixture and having the commercial Insulated Iron Powder Compounds (I.I.P.C.) considered as reference [10].

The main aim was to obtain improved mechanical properties, still maintaining the magnetic characteristics concerning the commercial Insulated Iron Powder Compounds (I.I.P.C.), taken as reference [10].

2 Materials and experimental procedures

The preliminary stage consists in the choice of ferromagnetic powder: several powders have been considered and tested and the choice focus on a high purity atomised iron powder, with an average grain size of 150 μm. The grains constitute the base material; however, they need to be covered with an insulation layer to limit the eddy currents. The adoption of a resin makes the correct mixture of powders easy to manufacture [10].

Two moulds have been used to press the powders: a cylindrical one, with a diameter of 40 mm, and a rectangular one, 55mm × 10 mm (suitable for the production of samples for the Charpy tests).

The preparation of the samples was according to what described in [10]; four different percentages for each resin have been investigated (0.2 - 0.1 - 0.075 and 0.05% in weight). The compound realised with 0.2% was taken as reference material [10] for both resins, which are identified with letter E for Epoxy and with letter P for phenolic.

The magnetic characterisation has been performed at room temperature through a magnetic toroidal test [20–23], by exciting the sample with a regulated magnetic flux. The measuring system is capable of providing a controlled sinusoidal flux waveform with very low harmonic content, without an excessive sample heating – even at high amplitudes – avoiding the need for a special cooling system. The whole measurement and acquisition system has been designed and implemented in our laboratories (Figure 1). The distorted absorbed current, typical of magnetic circuits, is compensated by subtracting harmonics, obtaining very sinusoidal waveforms, with a Total Harmonic Distortion lower than 1% for the voltage at the secondary winding and a far below 1% for the flux waveform. The automatic acquisition and process elaboration have been developed in LabView environment.

For the mechanical characterisation, Transverse Rupture Strength (or TRS) measurements were realised [9, 10, 24]; TRS is a three-point bending test, usually adopted for brittle materials; the test is based on the deformation of the specimen by slowly increasing the force until the material breaks.

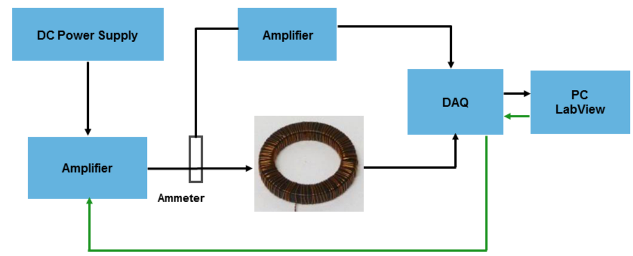

Figure 1: Scheme of magnetic measurement system

3 Results

The magnetic characteristics, *i.e.* the B-H curves, are reported in Figure 2 and Figure 3 for Epoxy and Phenolic samples respectively.

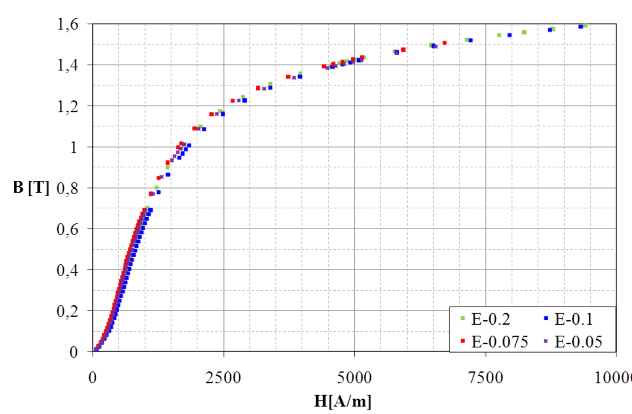

Figure 2: Magnetic characteristics for Epoxy SMC pressed at 800 Mpa

For epoxy samples, it is evident that the variation of binder does not particularly affect the magnetic characteristic (Figure 2). On the other hand, the reduction of the binder percentage improves the magnetic characteristics of phenolic SMC. The Phenolic reference material "P-0.2" shows the lowest magnetic behaviour (Figure 3).

To obtain quantitative information from magnetic characteristics, the magnetic flux density B at 5000 A/m

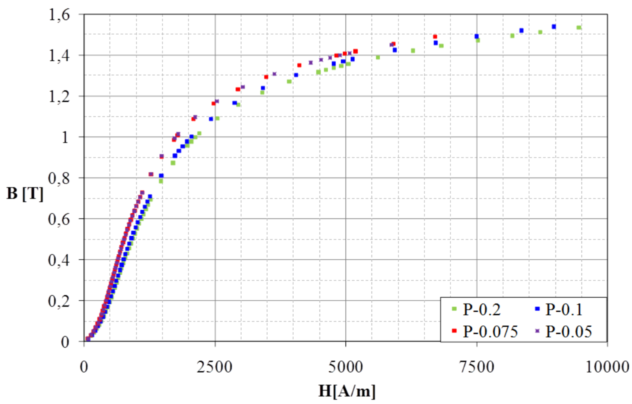

Figure 3: Magnetic characteristics of Phenolic SMC pressed at 800 MPa

has been detected for the different binder percentages at 800 MPa. The results for Epoxy SMC have confirmed that all values are fairly constant; this means that further improvements for magnetic characteristics cannot be obtained (Table 1). In the case of Phenolic SMC the magnetic flux density B at 5000 A/m increases for lower contents of binder (Table 1).

The maximum magnetic permeability has been determined from the data of B-H curves at 800 MPa and for different binder percentages (Table 1). For the Epoxy resin specimens, the highest magnetic permeability is obtained with the intermediate weight% of the binder (0.075%); further reduction in the Epoxy weight content (0.05%) causes a decrease in the permeability values.

Table 1: Magnetic induction B @ 5000 A/m and Maximum magnetic permeability for both typologies of samples

Resins	Samples	B @ 5000 A/m [T]	μ_{rMAX} [-]
Epoxy	E-0.2	1,426	533
	E-0.1	1,417	542
	E-0.075	1,427	567
	E-0.05	1,416	546
Phenolic	P-0.2	1,353	446
	P-0.1	1,372	462
	P-0.075	1,409	532
	P-0.05	1,406	533

The results shown in Figure 4 and Figure 5 are referred to the case of specific losses for 50Hz @ 1T. The lowest values have been obtained for binder percentage of 0.075, and as previously mentioned, for binder content of 0.05 the values worsen.

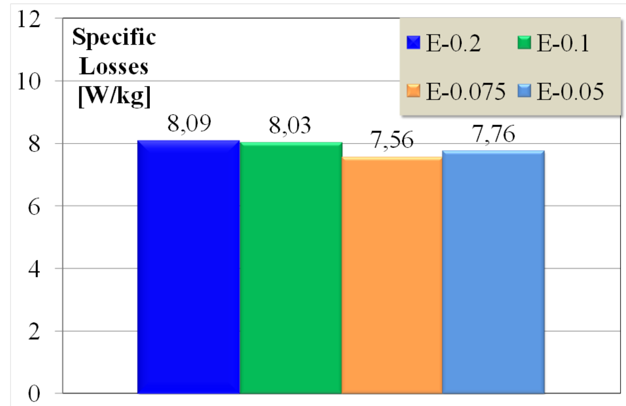

Figure 4: Specific iron losses for 50Hz @ 1T of epoxy samples

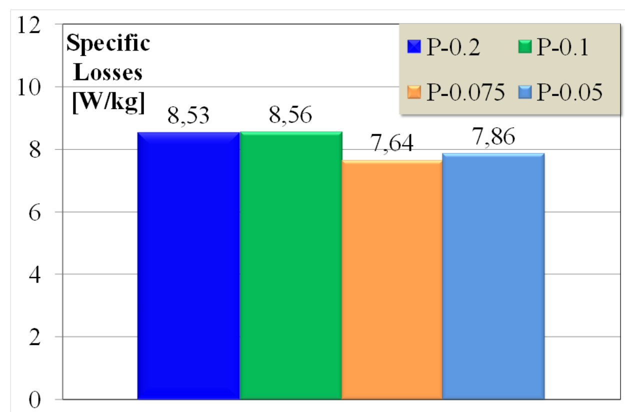

Figure 5: Specific iron losses for 50Hz @ 1T of phenolic samples

Mechanical properties have been determined for both typologies of resins; the results show that the mechanical performance decreases with the reduction of polymeric binder (Figure 6 and Figure 7): TRS values remain satisfactory up to 0.075% of binder content, and after that rapidly drop.

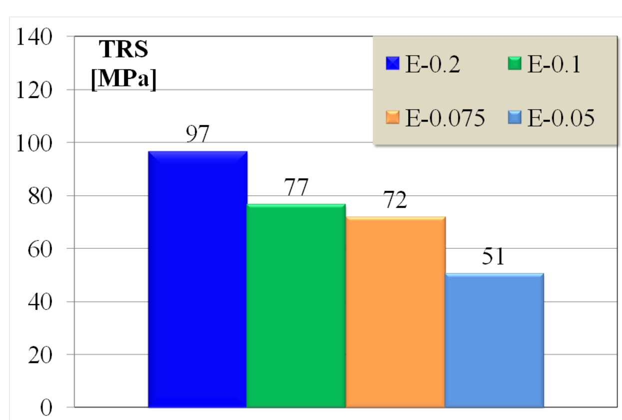

Figure 6: Mechanical strength of epoxy SMC

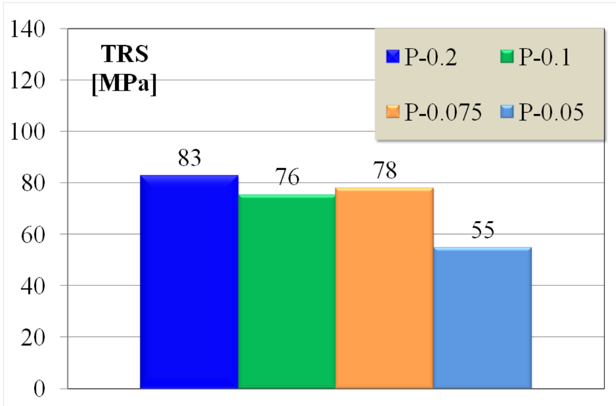

Figure 7: Mechanical strength of phenolic SMC

4 Conclusion

The proposed SMC materials have confirmed the possibility to obtain characteristics suitable for their adoption in the realisation on the magnetic circuits of electric machines.

The detected magnetic properties, particularly when using Epoxy as a binder, are of significant interest; on the other side, the obtained mechanical strength is slightly higher with respect to the values presented by similar commercial products available on the market.

Another important consideration regards the production process, which is easy for both resins; in particular, the low temperature values requested in the post pressure treatment allows to foresee a low production cost.

Particularly significant is the lower limit in the percentage of binder, 0.075%, adopted at the aim of maximising the magnetic characteristics, and still maintaining suitable mechanical prerogatives.

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