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New Soft Magnetic Composites for electromagnetic applications with improved mechanical properties

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The chance to move from 2D to 3D approach in the design of the electrical machines is made possible by the availability of Soft Magnetic Composites (SMC), iron based powders, insulated and pressed to realize shapes otherwise impossible with the traditional lamination sheets technology. Some commercial products are available on the market as "ready to press" powders, which presents good magnetic and energetic properties but are sometimes weak under the mechanical point of view; other products aim at improving this aspect but with considerable process complications and relative cost. The experience of the Authors in the realization of bonded magnets with the adoption of selected organic resins has been partly transferred in the research field of the SMC in order to investigate the possibility to obtain good mechanical properties maintaining the magnetic characteristics of the Insulated Iron Powder Compounds (I.I.P.C.) taken as reference. The paper presents the activity that has been carried out in the realization of SMC mixing iron powders and phenolic resin, in different weight percentages and mold pressures. The obtained results are considered satisfactory under the point of view of the compromise between magnetic and mechanical properties, considering also that the required productive process is simpler. The comparison of the obtained results with those related to commercial products encourages to carry on the research, also because of the reduced cost of the proposed SMC at parity (or better) performance. [http://dx.doi.org/10.1063/1.4943413]

I. INTRODUCTION

The magnetic cores of electric motors, transformers and actuators are usually realized by packs of magnetic sheets. Nowadays, thanks to the development of powder metallurgy, the possibility of using the magnetic powders in substitution of the laminations sheets has been introduced.[1,2] In general the adopted materials are named Soft Magnetic Composites, or SMC[3]; they are obtained by iron based powders covered with an insulating layer; good magnetic properties are obtainable.[4,5] The basic advantages obtainable by abandoning the classic laminated magnetic circuits technology and adopting magnetic powders is the possibility to radically change the design approach, from a 2D vision to a 3D design of the magnetic pattern[6]: the material is isotropic and can carry the flux in all directions with the same properties. In many cases the adoption of parts obtained by molding may be an interesting solution,[7] especially if the desired geometry presents complications when realized with magnetic sheets[8–12]; such elements may bring to a strong simplification in the production process.[13]

In the paper the adoption of a novel SMC material in place of I.I.P.C. available on the market is proposed by using common iron powders mixed together with organic resins: it's important to note that I.I:P.C taken as the reference is in practice the only material adopted for the applications; that justifies the choice to compare the SMC described in the paper with only one alternative

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product. In previous activities the Authors have experienced the adoption of resins to realize bonded magnets[14–16] and are now proposing the same resins to produce SMC.[17]

II. GOAL OF THE WORK

The goal of the work is to evaluate the magnetic and mechanical properties[18] of the proposed SMC and to compare them with the ones obtainable by means of the commercial product. The analysis is carried out also considering the process simplification[17] in terms of mechanical pressure[19,20] to be applied on the mold and in terms of post pressure thermal treatment[21]; economic aspects[22] are marginally considered at this stage of the research activity, but are anyhow presented as an interesting evaluating factor.

In the paper several SMC productions are considered, using different percentages of plastic binder and different compaction pressures. The experimental results showed similar magnetic characteristics and better mechanical performance with respect to the basic I.I.P.C. product; this last is realized with pure iron powder particles coated with a very thin electrically insulated layer. The SMCs proposed in the paper are made starting from a common ferromagnetic powder, without the presence of any insulating layer on each individual grain; the basic idea is the addition of an organic binder with the function of keeping together the grain structure, and of providing electrical insulation. In the present research activity the attention has been focused on the most suitable resin to be adopted; the opportunity to work together with the plastic research group operating in the Alessandria campus of Politecnico di Torino has made possible to select few resins in the very wide panorama.[14,17] In particular are here presented the SMCs realized with phenolic resins, well known and widely adopted in the realization of metallic compounds, particularly in the field of the car brakes, testifying high resistance to mechanical stress. The proposed mixture of powder is easy to manufacture[17] and doesn't require a dedicated process as spraying or resin bath, but just a good mixing operation, and doesn't require long and particular heat treatments at high temperatures: 150 °C for short time instead of 500 °C for a longer time normally prescribed. For all these reasons the material and it's process are enough cost-effective.

The investigation of the dependence of the magnetic and mechanical properties on the different binder percentages and of the pressure adopted in the sample realization has been made possible by the capability of producing the samples in our own laboratories according to the specific requirements. In such way the realization process of the samples is totally under control, starting from the powder mixing, up to the wounded toroid structure for magnetic measurements (Fig. 1) and for mechanical tests (Fig. 4(a)).

The experimental results will be compared with the commercial I.I.P.C. product well known on the market and taken as a reference. It must be underlined that there is not the ambition to "invent" something that does not exists, but just the consciousness that the research could explore further margins of the resulting magnetic and mechanical properties.

III. SAMPLES REALIZATION AND EXPERIMENTAL PROCEDURES

The activity started from the selection of the ferromagnetic powder that could best fit the application field; several powders have been considered and tested, and the choice fell on a powder with high iron content and irregular granules, usually adopted in applications for which high densities are required. Such granules are not ready to use, but constitute the base material with the necessity to provide an insulation layer. As already mentioned, in this paper the adoption of a phenolic resin is proposed: the choice of such a kind of resin comes from the considerations about its common adoption in applications for which the mechanical resistance is a fundamental requirement, such as for example the production of car brakes.

The phenolic resin is in the form of powder (Fig. 1(a)) and presents easiness to be mixed with the ferromagnetic component (Fig. 1(b)) to electrically insulate the ferromagnetic grains and guarantee mechanical resistance. The obtained mixture is then used to prepare the discoidal samples for the characterization[18,23]; two variables have been considered: the percentage of the phenolic binder

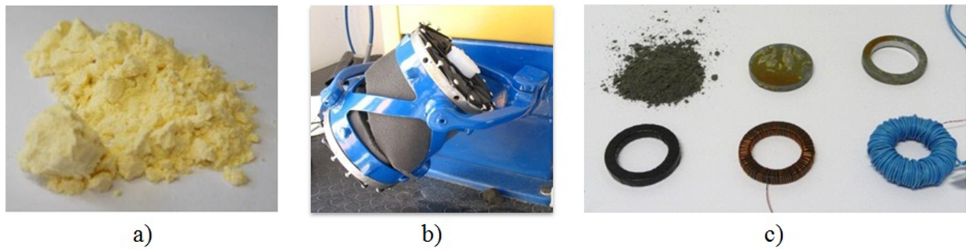


FIG. 1. a) phenolic resin, b) turbula mixer, c) samples realization sequence.

(0.2-0.5-0.75-1-1.5-2%) and the pressure on the cylindrical mold (400-500-600-700 MPa). The disks are then subjected to reticulation process for 30 minutes at 150°C, and finally, by mechanical milling, the toroid samples,[23,24] ready to be wounded for the electromagnetic tests, are obtained; the different stages of the production process are synthetized in Fig. 1(c), from the powder mixing to the wounded toroid. Also special samples for the mechanical tests have been prepared. The samples are classified with a code reporting the information regarding the type of resin (P for Phenolic), the percentage in weight of the plastic binder and the compacting pressure in MPa; as an example "P-1-700" identifies a toroid with Phenolic resin at 1% in weight, pressed at 700 MPa.

The magnetic characterization is performed with the well known "transformer approach", where two windings are wrapped around the toroidal magnetic core (Fig. 1(c)): the first gives magnetization to the circuit with a current proportional to the magnetic field H, and the second winding, realized with a very thin copper wire accurately wrapped very close to the magnetic core, detects the induced voltage, proportional to the magnetic flux density B. The supply and measurement system has been designed in our laboratories. The requested sinusoidal waveform are normally obtained with special converters having consistent filtering stage at the output terminals in order to guarantee a low harmonic content; in our case the sinusoidal supply has been realized with the adoption of a linear amplifier (that makes it cheaper) providing a Total Harmonic Distortion (THD) lower than 1%; a data acquisition board is driven by a devoted LabView code to automatically acquire data and process them to obtain the magnetic information.

In Fig. 2 the hysteresis loop is reported as an example of how the introduction of the phenolic resin impacts on the magnetic behavior of the ferromagnetic powder.

One of the main goals of the present activity is the improvement of the mechanical properties of the SMC; different types of tests can be adopted for the mechanical characterization of powder metallurgy products: bending tests have been preferred to evaluate the strength of our samples, having low ductility and definable such as highly porous materials.[18,23] The mechanical properties can be expressed through the Transverse Rupture Strength (or TRS), with a three point bending

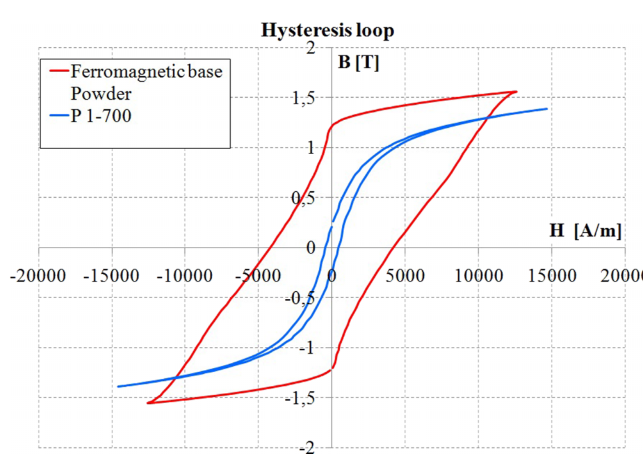


FIG. 2. Hysteresis loop of the proposed SMC in comparison with the base material one.

test, typically adopted for brittle materials; the test is based on the deformation of the specimen by slowly increasing the force until the material failure occurs in the area of tension/stress, as shown in Fig. 4(a).

The stress originates in the cross section of the specimen when subjected to a bending moment, generated by transverse forces acting parallel to the plane of the cross section. The bending strength TRS can be defined as the maximum bending stress in the tested specimen at the time of its failure, and is given by the expression:

$$TRS = \frac{3 \cdot P \cdot L}{2 \cdot w \cdot t^2}$$

where P is the load of the tested specimen determined by force gauge at the time of specimen failure, L is the distance between the supporting rollers, w is the width perpendicular to the load direction, and t is the thickness parallel with the load direction[25]; during the experimental measurement the instrument measures the load P and calculates the TRS.

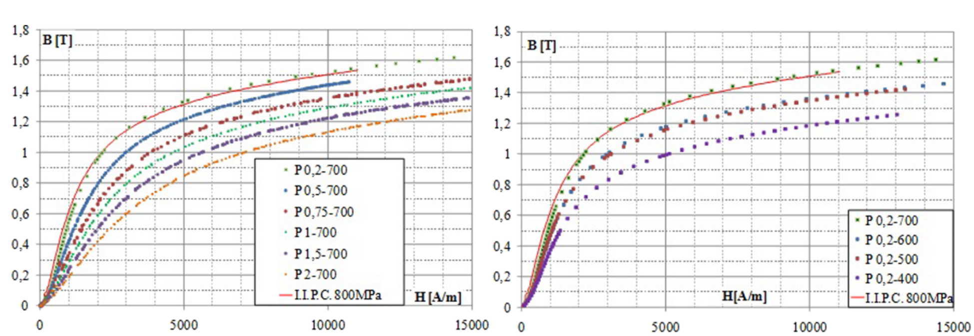
IV. COMMENTS ON THE EXPERIMENTAL ACTIVITY

The great variety of SMC samples, obtained with the different binder percentages and mold pressures, have been subjected to a huge experimental activity, comparing the results with those obtainable with the commercial I.I.P.C. A complete analysis must take into account the magnetic and mechanical properties at the same time, and a good compromise has to be found between the two.

At the aim some operating phases have been realized; with different binder percentages (from 0.2% to 2%) and different pressures (from 400 to 700 MPa) both the samples necessary for the electromagnetic measurements and the ones necessary for the mechanical tests have been prepared. A long series of measurements have been performed; for what it concerns the results accuracy, a ±1% of error has to be considered for the adopted procedures. But it is opportune to underline that the obtained data constitute a series of confrontations among results obtained with the same procedures and the same apparatus; then the confrontation results maintain their validity, apart from their absolute accuracy.

The influence of the SMC binder percentage on the magnetic properties is presented in Fig. 3(a): the magnetic flux densities B, referred to the magnetic field H, for SMCs pressed at 700 MPa are compared. As expected it is well evident that the reduction of the resin content improves the magnetic properties. Under this point of view the results obtained with 0.2% of phenolic resin has been considered satisfactory as comparable with the commercial product characteristics; it can be also underlined that the I.I.P.C. considered as a reference has been pressed at 800 MPa.

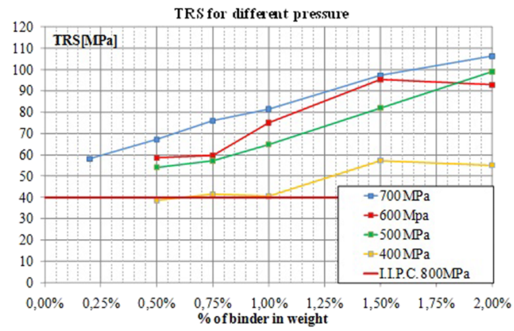
The effect of the compacting pressure on the magnetic behavior is not univocal, but it is related to the percentage content of binder; the higher is the resin content the lower is the effect



a) b)

FIG. 3. Magnetic characteristics for different binder % at a compacting pressure of 700 MPa (a) and for different pressures with binder content of 0.2% (b).

a)



b)

FIG. 4. - a) Mechanical TRS test bench - b) Mechanical performance TRS as a function of the binder percentage and transverse rupture strength; the TRS of the I.I.P.C. is indicated as a constant value line.

of the pressure increment on the mold. As pointed out before, the best results are obtained for low resin percentage: in such case the increment of the pressure plays an important role in the final characteristics of the SMC sample (Fig. 3(b)).

The results of the bending tests confirm the logic impression that both the increment of the resin content and the increment of the pressure play an important role on the mechanical properties. In Fig. 4(b) the bending tests results are shown: it is interesting to observe that all the SMC samples present better performance with respect to I.I.P.C. It seemed that the results could be considered extremely satisfactory.

V. CONCLUSIONS

The referred activity has brought to interesting results: the proposed SMC, obtained with a phenolic resin, has presented good magnetic and mechanical properties; these ones are much better than I.I.P.C. ones. The exploration of the different binder percentages and process pressure has put also in evidence how the final magnetic characteristics can be modulated according to the specific requirements. The activity of characterization is still continuing, especially as regards the evaluation of the specific losses.[26,27] The prosecution of the activity research would bring in the near future to the realization of prototypes or parts of prototypes.[28]

As final considerations, some comments regarding the costs are here presented. Considering as reference the basic I.I.P.C. cost, the proposed magnetic composite is slightly cheaper, even if the cost of the resin significantly impact on the final product; on the other hand, a proper comparison should be made with reference to the I.I.P.C. presenting improved mechanical properties , comparable to those presented in Fig. 4(b): in this case the proposed SMC cost is about 50% cheaper than the commercial one. It must also be remembered that the global process is simpler and cheaper both in the mold and in the successive thermal treatment.

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