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ABSTRACT

In the field of electrical machines, the actual research activities mainly focus on improving the energetic aspects; for this reason, new magnetic materials are currently investigated and proposed, supporting the design and production of magnetic cores. The innovative aspects are related to both hard and soft magnetic materials. In the case of permanent magnets, the use of NdFeB bonded magnets represents a good solution in place of ferrites. For what concerns the soft magnetic materials, the adoption of Soft Magnetic Composites (SMCs) cores permits significant advantages compared to the laminated sheets, such as complex geometries and reduced eddy currents losses. SMC materials are ferromagnetic grains covered with an insulating layer that can be of an organic or inorganic type. The proposed study focuses on the impact of the particle size and distribution on the final material properties. The original powder was cut into three different fractions, and different combinations have been prepared, varying the fractions percentages. The magnetic and energetic properties have been evaluated in different frequency ranges, thus ranking the best combinations. The best specimens were then tested to evaluate the mechanical performances. The preliminary results are promising, but deeper analysis and tests are required to refine the selection and evaluate the improvements against the original composition taken as a reference.

I. INTRODUCTION

Magnetic materials play an essential role in several industrial applications, such as electromechanical devices, electronic, automotive, energy production, refrigeration, magnetic separators, household equipment, etc. Most of the cited applications are based on the use of electrical machines, which are principally made with soft and hard magnetic materials. In the last years deeper and deeper studies, about the development of new magnetic materials, have been carried out to improve the performances of the electrical machines.[1,2] The primary requirement concerned the improvement of the efficiency with a higher weight-volume ratio.[3] On the other hand, also the robustness became a main parameter. Different magnetic materials, both soft and hard, have been therefore studied and proposed to substitute the traditional ones.[4,5]

For the flux production in electrical machines, the adoption of bonded permanent magnets allows getting magnetic characteristics better than hard ferrites, exploiting the polymeric moulding technology (injection and compression).[6–9] Moreover, the possibility to make complex shaped magnets gives an advantage compared to sintered NdFeB magnets, which are fragile and restricted to regular form.[10–13]

In the case of soft magnetic materials, the traditional laminated steel is not suitable to satisfy the innovative design criteria of particular electrical machines, such as the axial flux machines (AFM),[14–16] the transverse flux machines (TRM),[17] the claw pole machines (CPM),[18] etc.[19] All mentioned machines share a common property: the complex magnetic core geometry, which requires a 3D path for the magnetic flux. Since the laminated steel permits to guide the magnetic flux only in 2D, new magnetic materials often replace them, such as the Soft Magnetic Composites (SMC).[20–22] Such magnetic materials are made with a ferromagnetic base powder, whose particles are covered with an electrically insulating layer to limit the energy dissipation due to eddy current losses. In general, the layers can be of organic or inorganic types, and different techniques are adopted to prepare such coatings: mixing, deposition, curing, sol-gel, co-precipitation and others.[23–30] Usually, the organic layers consist of resins,[31,32] while the inorganic ones are metallic oxides, ferrite, aluminium, silicon and others.[33,34] SMCs present further advantages compared to laminated steels: low eddy currents, low specific losses at medium-high frequencies and more compacted machine geometries; accordingly higher power densities for the same dimension compared to the traditional radial flux machines (RFM) are possible.[16] The low mechanical strength of the material is the weak point.

Other promising materials are the so-called Hybrid Magnetic Composites (HMC), consisting of both soft and hard magnetic materials powders mixed, in which the mechanical solidity is given by a polymeric binder.[35] HMCs are particular permanent magnets with very low coercivity and can be used in substitution of AlNiCo[36] and ferrite magnets mostly in sensor applications.[37]

II. AIM OF THE WORK

In the recent past, the Authors proposed and analysed different magnetic materials, both permanent magnets and SMCs,[6,31,38] focusing the activity in the research of their improved performance. The development of axial flux motors needs SMC materials with excellent properties, which can be subdivided in magnetic, energetic and mechanical performances. For what concerns the magnetic properties, good permeability (around 500) and BH curve (magnetic induction B at 5000 A/m over 1.3 T) are required. Regarding the energetic aspects, the iron losses depend on the operating frequency instead and must be kept as low as possible. The mechanical properties limit the use of SMC materials in several industrial applications; in general, the mechanical strength (“Transverse Rupture Strength” – TRS) is about 40 MPa for common commercial SMC products. On the other hand, the commercial materials with values of 100 MPa and more are expensive and made with complicated processes or tested only at the laboratory level.

In this work, the principal energetic aspects will be evaluated as a function of the particle size.[39–42] The iron losses in SMCs can be divided into three components: the more common hysteresis and eddy currents losses and the last introduced excess losses,[43,44] the latter being negligible in laminated steels and bulk/massive ferromagnetic materials.

Different particle fractions of the high-purity reference ferromagnetic powder were analysed (0.04 wt% oxygen content).

III. SAMPLE PREPARATION AND PROCEDURE DESCRIPTION

The reference iron powder has been sieved in three different normalized cuts: small (below 63 μm), medium (between 63 and 125 μm) and large (over 125 μm). The reference powder, as available from the producer, has approximately the following fraction components: large (L) 30 wt%, medium (M) 50 wt% and small (S) 20 wt%.

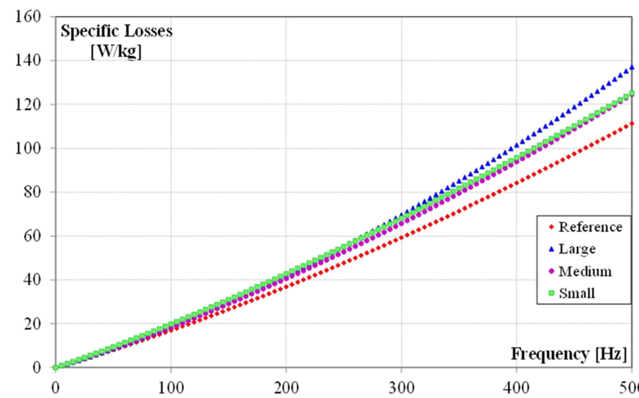

FIG. 1. Specific losses at 1 T of large, medium and small fractions compared to the reference case.

Different compounds were obtained for every fraction, by adding 0.2 wt% of epoxy resin binder (organic layer). The resulting systems were compacted at 700 MPa and cured in air at 150 °C for 30 minutes. The resin addition provides electrical insulation and the necessary mechanical strength. The binder percentage affects both the magnetic and energetic properties of the composite,[23,31] but, due to the low annealing temperature, no metallurgical diffusion process occurs between iron and binder. The energetic performances of all fractions had previously been analysed in a recent work,[45] in which the reference case remained the best solution, as shown in Fig. 1. It has to be pointed out that the small fraction is preferable when working at a high operating frequency, while the large one is best at low frequencies (<100 Hz). From an accurate analysis, the small particles reduce the eddy currents losses while the large ones lower the hysteresis losses. The medium fraction optimizes both conditions in the analyzed frequency range. The loss curves of the small and medium fractions are very near at 500 Hz, but the medium one would grow quicker by further increasing the frequency.

In a subsequent phase, nine different powder mixes were composed with the three initial fractions, obtaining nine different sizes distributions. The identification name is proposed in the following way: Epoxy SMC L%.M%.S%, for instance, Epoxy SMC 30.20.50. All samples have been prepared with the same polymeric binder (epoxy 0.2 wt%) and pressed at 700 MPa. The Table I shows the new fractions.

IV. EXPERIMENTAL RESULTS

The measurement of the magnetic quantities is performed with a “transformer approach” on Soft Magnetic Material toroidal specimens made on purpose. The magnetization is provided using a controlled source which guarantees distortion compensation of the magnetic flux waveform (Total Harmonic Distortion below 1%) in a frequency range from 0.25 Hz to 2000 Hz. The system and methods are completely outlined in a previous work.[31] The system is capable of measuring all the magnetic and energetic properties for a single frequency or in a frequency range.

Since this work focuses primarily on the energetic aspects of the obtained materials, only a brief reference on the magnetic properties and the mechanical strength is presented.

TABLE I. Composition of proposed SMCs and magnetic characteristics at 50Hz: maximum magnetic permeability (μ_{max}), magnetic induction B at 5000 A/m ($B_{5000\ A/m}$) and magnetic field at 1T ($H_{1\ T}$).

Name	% Large	% Medium	% Small	μ_{max} 50 Hz [-]	$B_{5000\ A/m}$ 50 Hz [T]	$H_{1\ T}$ 50 Hz [A/m]
Epoxy SMC 70.30.0	70	30	0	539	1.38	1823
Epoxy SMC 70.0.30	70	0	30	500	1.35	1992
Epoxy SMC 50.30.20	50	30	20	527	1.37	1841
Epoxy SMC 50.20.30	50	20	30	488	1.33	2043
Epoxy SMC 30.70.0	30	70	0	541	1.37	1819
Epoxy SMC 30.20.50	30	20	50	471	1.34	2076
Epoxy SMC 30.0.70	30	0	70	465	1.33	2102
Epoxy SMC 0.70.30	0	70	30	488	1.37	1955
Epoxy SMC 0.30.70	0	30	70	426	1.30	2367
Reference 30.50.20	**30**	**50**	**20**	**510**	**1.41**	**1882**

A. Magnetic properties

Magnetic tests were performed at 50 Hz to have a complete overview of the magnetic properties of all the compounds. The results showed better magnetic properties – mainly regarding the magnetic permeability – for the powders with higher percentages of large particles, as shown in Table I. From this analysis would emerge that the fractions with the large particles would be the right choices, but the detected data are not enough to properly evaluate the actual performance of the particles sizes distributions. The reference powder magnetic behaviour remains slightly better than the investigated compositions; therefore for a correct selection of the particles sizes distribution other tests need to be performed.

B. Energetic properties

The tests were performed at frequencies up to 500 Hz. For every SMC sample, the specific iron losses at 1 T were detected at different frequencies, as reported in the Fig. 2. Three discrete frequency ranges were considered as a function of the typical operating conditions: below 100 Hz, between 100 Hz and 250 Hz, and between 250 Hz and 500 Hz. It is, therefore, possible to order the samples in a ranking for any specific frequency range. In Table II each system is identified by a different color. It is possible to note that the large fraction has the lowest iron losses at low frequency, but for the same systems, the losses increase rapidly over frequency. On the

TABLE II. Specific iron losses ranking as a function of frequency.

	Frequency Range		
Ranking	<100 Hz	100-250Hz	250-500Hz
1	**50.30.20**	**50.30.20**	**50.30.20**
2	*30.70.0*	*30.70.0*	*0.70.30*
3	**Reference**	*0.70.30*	*30.0.70*
4	*0.70.30*	**Reference**	**Reference**
5	70.30.0	*30.0.70*	30.20.50
6	70.0.30	30.20.50	*30.70.0*
7	*30.0.70*	0.30.70	0.30.70
8	30.20.50	70.0.30	70.0.30
9	50.20.30	50.20.30	50.20.30
10	0.30.70	70.30.0	70.30.0

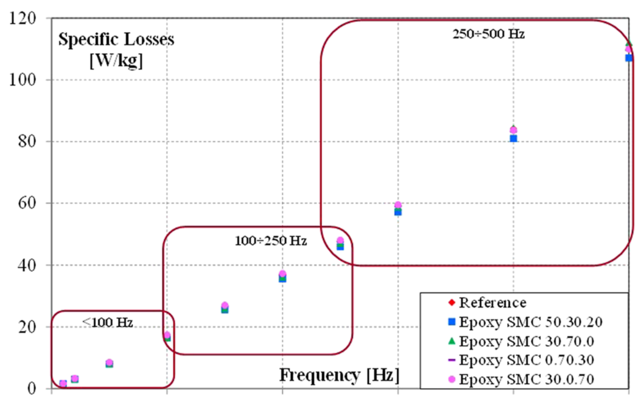

FIG. 2. Specific iron losses at 1 T as the function of frequency: different considered frequency range.

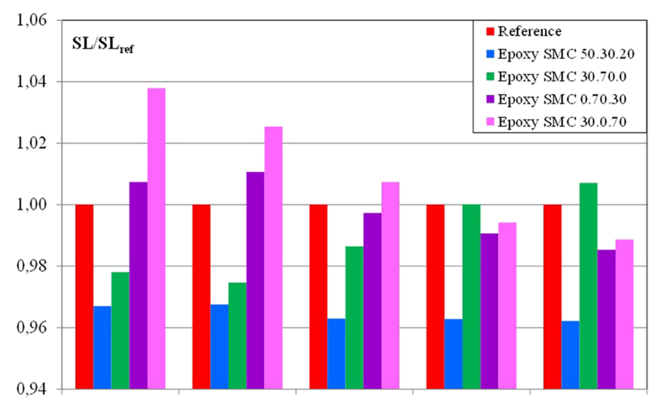

FIG. 3. Specific iron losses SL (at different frequencies normalized to the reference compound).

TABLE III. Mechanical strength of proposed SMCs and reference case.

Composition	Reference	Epoxy SMC 50.30.20	Epoxy SMC 30.70.0	Epoxy SMC 0.70.30	Epoxy SMC 30.0.70
TRS [MPa]	85	47	71	51	39

other hand, the small fraction shows the opposite behaviour: the systems in which it is predominant have the lowest iron losses at high frequency. Therefore the best solution involves correctly balancing the medium sized particles with the other two fractions. The Epoxy SMC 50.30.20 was the best for all frequencies. Moreover, three other distributions, among the top three for every frequency range, have been chosen for further evaluation: Epoxy SMC 30.70.0, Epoxy SMC 0.70.30, Epoxy SMC 30.0.70.

The results of the specific iron losses at 1 T of all the selected SMC samples were expressed normalising the data to the reference powder. In Fig. 3 the Epoxy SMC 50.30.20 shows the best energetic properties for all the considered frequencies, while the Epoxy SMC 30.70.0 (italic in Table II) gives good results only at the lowest frequencies, getting worse by increasing the frequency. Contrarily, the Epoxy SMC 0.70.30 (italic in Table II) and Epoxy SMC 30.0.70 (italic in Table II) show the lowest iron losses at high frequencies, but the worst at low frequency. In any case, the test results put into evidence that the energetic behaviour of the reference SMC is averagely worse of many of the proposed compositions for all the considered frequencies; the difference, compared to the best result (Epoxy SMC 50.30.20), is of about 4%.

C. Mechanical properties

The samples of all systems were mechanically characterised with the three-point flection test,[31,38] obtaining the material's TRS value, as reported in Table III. The mechanical strength is maximum for the original reference powder. Therefore the mechanical properties seem to depend on the medium and large particles sizes balance mainly. The results should be anyway considered together with further micrographic analyses of the fractures to obtain relevant information.

V. CONCLUSIONS

The ferromagnetic powder, as supplied by the producer, has been sieved in three different fractions. From such fractions, nine powder systems were composed having different particles sizes distributions. After that, the SMC samples were obtained by adding the organic layer (epoxy resin 0.2 wt%). The magnetic, energetic and mechanical properties have been detected and compared to those of the reference SMC (original powder). As expected, the large particles affect the magnetic and energetic performances at low frequencies, while the small particles have a positive effect at higher frequencies. The best energetic results were obtained with the following particles sizes fractions 50.30.20, which is better than the reference SMC of about 4%. The mechanical strength depends on the balancing of the medium and large particles sizes fractions. The reference case has, however, the best mechanical properties.

The work highlights the importance of the particles size in determining the SMC performances. In future activities, other powder mixes will be considered, and a careful study of the mechanical strength as a function of the granulometry will be carried out. Hopefully, it will be possible to optimise the SMC granulometry starting from the design operating frequency.

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