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The effect of particle size on the core losses of soft magnetic composites

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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.

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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.10–15

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).\textsuperscript{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.\textsuperscript{23-30} Usually, the organic layers consist of resins,\textsuperscript{31,32} while the inorganic ones are metallic oxides, ferrite, aluminium, silicon and others.\textsuperscript{23,34} 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.\textsuperscript{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.\textsuperscript{35} HMCs are particular permanent magnets with very low coercivity and can be used in substitution of AlNiCo\textsuperscript{46} and ferrite magnets mostly in sensor applications.\textsuperscript{47}

II. AIM OF THE WORK

In the recent past, the Authors proposed and analysed different magnetic materials, both permanent magnets and SMCs,\textsuperscript{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.\textsuperscript{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,\textsuperscript{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%.

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,\textsuperscript{23,33} 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,\textsuperscript{37} 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.\textsuperscript{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 ($\mu_{\text{max}}$), magnetic induction B at 5000 A/m ($B_{5000 \text{ A/m}}$) and magnetic field at 1T ($H_{1 \text{T}}$).

| Name           | % Large | % Medium | % Small | $\mu_{\text{max}}$ 50 Hz [-] | $B_{5000 \text{ A/m}}$ 50 Hz [T] | $H_{1 \text{T}}$ 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                            | 2043                        |
| Epoxy SMC 50.20.30 | 50      | 20       | 30      | 488                          | 1.33                            | 1819                        |
| Epoxy SMC 30.70.0 | 30      | 70       | 0       | 541                          | 1.37                            | 1955                        |
| 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                        |
| 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
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 0.30.70.

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 III) gives good results only at the lowest frequencies, getting worse by increasing the frequency. Contrarily, the Epoxy SMC 0.70.30 (italic in Table III) and Epoxy SMC 30.0.70 (italic in Table III) 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 flexion test, 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.

### REFERENCES

1. N. Fernando and F. Hanin, “Magnetic materials for electrical machine design and future research directions: A review,” IEEE IEMDC Conf. Proc., Miami (USA), 21–24 May 2017.

2. A. Krings, M. Cossette, A. Tenconi, J. Soulard, A. Cavagnino, and A. Boglietti, “Magnetic materials used in electrical machines,” IEEE Industry Applications Magazine, 21–28 (2017).

3. M. Peter, J. Fleischer, F. S. L. Blanc, and J. P. Jastrzembski, “New conceptual lightweight design approaches for integrated manufacturing processes: Influence of alternative materials on the process chain of electric motor manufacturing,” IEEE EDPC Conf. Proc., Nuremberg (Germany), 29–30 October 2013.

4. Y. Oda, M. Kohno, and A. Honda, “Recent development of non-oriented electrical steel sheet for automobile electrical devices,” J. Magnetism and Magnetic Materials 320, 2430–2435 (2008).

5. P. Beckley, “Modern steels for transformers and machines,” IEEE J. Engineering Science and Education 8, 149–159 (1999).

6. L. Ferraris, P. Ferraris, E. Pošković, and A. Tenconi, “Theoretic and experimental approach to the adoption of bonded magnets in fractional machines for automotive applications,” IEEE Trans. On Ind. Electron. 59, 2309–2318 (2012).

7. S. X. Bai, H. Zhang, L. Lv, K. Chen, S. Li, X. P. Yang, W. J. Jia, and H. N. Cai, “Progress of research on bonded Nd–Fe–B magnet,” J. Iron and Steel Research 13, 489–493 (2006).

8. L. Ferraris, P. Ferraris, E. Pošković, and A. Tenconi, “PM fractional machines adopting bonded magnets: Effect of different magnetisations on the energetic performance,” IEEE ENERGYCON Conf. Proc., Florence (Italy), 9–12 September 2012, pp. 113–120.

9. L. Ferraris and E. Pošković, “Bonded magnets for brushless fractional machines: Process parameters effects evaluation,” IEEE IICON Conf. Proc., Vienna (Austria), 10–13 November 2013, pp. 2632–2637.

10. T. Gundogdu and G. Komurog, “The impact of the selection of permanent magnets on the design of permanent magnet machines—A case study: Permanent magnet synchronous machine design with high efficiency,” Przegląd Elektrotechniczny R89, 103–108 (2013).

11. H. Nakamura, “The current and future status of rare earth permanent magnets,” Scripta Materialia (in press).

12. P. C. Dent, “Rare earth elements and permanent magnets,” J. Appl. Phys. 111, 07A721 (2012).

13. B. E. Davies, R. S. Mottram, and I. R. Harris, “Recent developments in the sintering of NdFeB,” Materials Chemistry and Physics 67, 272–281 (2001).

14. F. Giulii Capponi, G. De Donato, and F. Caricchi, “Recent advances in axial-flux permanent-magnet machine technology,” IEEE Trans. On Ind. Appl. 48, 2190–2205 (2012).

15. S. Kahourzade, N. Ertugrul, and W. L. Soong, “Investigation of emerging magnetic materials for application in axial-flux PM machines,” IEEE ECCE Conf. Proc., Milwaukee (USA), 18–22 September 2016.

16. F. Franchini, E. Pošković, L. Ferraris, A. Cavagnino, and G. Brameradorfer, “Application of new magnetic materials for axial flux machine prototypes,” IEEE IEMDC Conf. Proc., Miami (USA), 21–24 May 2017.
AIP Advances 9, 035224 (2019); doi: 10.1063/1.5080079

B. Zhang, T. Epskamp, M. Doppelbauer, and M. Gregor, “A comparison of the transverse, axial and radial flux PM synchronous motors for electric vehicle,” IEEE IEVC Conf. Proc., Florence (Italy), 17–19 December 2014.

R. P. Deodhar, A. Pride, and J. J. Bremner, “Design method and experimental verification of a novel technique for torque ripple reduction in stator claw-pole PM machines,” IEEE Trans. on Ind. Appl. 51, 3743–3750 (2015).

Y. Dou, Y. Guo, and J. Zhu, “Investigation of motor topologies for SMC application,” IEEE IECMS Conf. Proc., Seoul (South Korea), 8–11 October 2007, pp. 695–698.

K. J. Sunday and M. L. Taheri, “Soft magnetic composites: recent advancements in the technology,” Metal Powder Report 72, 425–429 (2017).

A. Schoppa, P. Delabre, E. Holzmann, and M. Sigl, “Magnetic properties of soft magnetic powder composites at higher frequencies in comparison with electrical steels,” IEEE EDPC Conf. Proc., Nuremberg (Germany), 29–30 October 2013.

M. Strečkova, R. Bures, M. Faberova, L. Medvecky, J. Fuzer, and P. Kollar, “A comparison of soft magnetic composites designed from different ferromagnetic powders and phenolic resins,” Chinese J. of Chemical Engineering 23, 736–743 (2015).

L. Ferraris, E. Pošković, and F. Franchini, “New soft magnetic composites for electromagnetic applications with improved mechanical properties,” AIP Advances 6, 056209 (2016).

A. Perigo, S. Nakahara, Y. Pittini-Yamada, Y. de Hazan, and T. Graule, “Magnetic properties of soft magnetic composites prepared with crystalline and amorphous powders,” J. Magnetism and Magnetic Materials 323, 1938–1944 (2011).

S. Wu, A. Sun, W. Xu, Q. Zhang, F. Zhai, P. Logan, and A. A. Volinsky, “Iron-based soft magnetic composites with Mn-Zn ferrite nanoparticle coatings obtained by sol-gel method,” J. Magnetism and Magnetic Materials 324, 3899–3905 (2012).

Y. Peng, Y. Yi, L. Li, J. Yi, J. Nie, and C. Bao, “Iron-based soft magnetic composites with Al2O3 insulation coating produced using sol-gel method,” Materials and Design 109, 390–395 (2016).

Y. Peng, Y. Yi, L. Li, H. Ai, X. Wang, and L. Chen “Fe-based soft magnetic composites coated with NiZn ferrite prepared by a co-precipitation method,” J. Magnetism and Magnetic Materials 428, 148–153 (2017).

K. K. Papynov, O. O. Shichalin, A. A. Belov, A. S. Portnyagin, V. Yu. Mayorov, E. A. Gridasova, A. V. Golub, A. S. Nepomnyashii, I. G. Tananaev, and V. A. Avramenko, “Synthesis of nanostructured iron oxides and new magnetic ceramics using sol-gel and SPS techniques,” AIP Conference Proceedings 1809, 020043–1–020043–14 (2017).

T. Schaffer, J. Burghaus, W. Pieper, F. Petzdolt, and M. Busse, “New concept of Si–Fe based sintered soft magnetic composites,” Powder Metallurgy 58, 106–111 (2015).

Y. Peng, J. Nie, W. Zhang, C. Bao, J. Ma, and Y. Cao, “Preparation of soft magnetic composites for Fe particles coated with (NiZn)Fe2O4 via microwave treatment,” J. of Magnetism and Magnetic Materials 395, 245–250 (2015).

M. Actis Grande, L. Ferraris, F. Franchini, and E. Pošković, “New SMC materials for small electrical machine with very good mechanical properties,” IEEE Trans. On Ind. Appl. 54, 195–203 (2018).

R. Bureš, M. Strečkova, M. Faberova, P. Kollar, and J. Fuzer, “Advances in powder metallurgy soft magnetic composite materials,” Arch. of Metallurgy and Materials 62, 1149–1154 (2017).

G. Zhao, C. Wu, and M. Yan, “Enhanced magnetic properties of Fe soft magnetic composites by surface oxidation,” J. Magnetism and Magnetic Materials 399, 51–57 (2016).

W. Ding, L. Jiang, Y. Liao, J. Song, B. Li, and G. Wu, “Effect of iron particle size and volume fraction on the magnetic properties of Fe/silicate glass soft magnetic composites,” J. Magnetism and Magnetic Materials 378, 232–238 (2015).

F. Franchini, F. Franchini, and E. Pošković, “Hybrid magnetic composite (HMC) materials for sensor applications,” IEEE SAS Conf. Proc., Catania (Italy), 20–22 April 2016, pp. 134–139.

Q. Xing, M. K. Miller, L. Zhou, H. M. Dillon, R. W. McCallum, I. E. Anderson, S. Constantinides, and M. I. Kramer, “Phase and elemental distributions in Alnico magnetic materials,” IEEE Trans. on Magn. 49, 3314–3317 (2013).

L. Ferraris, E. Pošković, and F. Franchini, “Study of the compositions of hybrid magnetic composite (HMC) materials for sensor applications,” IEEE EPE ECCE Europe Conf. Proc., Riga (Latvia), 17–21 September 2018, pp. 1–P.10.

F. Franchini, E. Pošković, F. Franchini, and M. Actis Grande, “A New Soft Magnetic Composites material for electrical machine: improvement of mechanical properties with high molding pressure,” EPMA EURO PM2017 Conf. Proc., Milan (Italy), 1–5 October 2017.

H. Shokrollahi and K. Janghorban, “The effect of compaction parameters and particle size on magnetic properties of iron-based alloys used in soft magnetic composites,” Materials Science and Engineering B 134, 41–43 (2006).

M. Anhalt, “Systematic investigation of particle size dependence of magnetic properties in soft magnetic composites,” J. Magnetism and Magnetic Materials 320, e366–e369 (2008).

A. H. Taghvaei, H. Shokrollahi, M. Ghaffari, and K. Janghorban, “Influence of particle size and compaction pressure on the magnetic properties of iron-phenolic soft magnetic composites,” J. of Physics and Chemistry of Solids 71, 7–11 (2010).

L. Ferraris, E. Pošković, F. Franchini, M. Actis Grande, and R. Budulský, “Effect of granulometry and oxygen content on SMC magnetic properties,” Acta Metallurgica Slovaca 23, 356–362 (2017).

Z. Bircáková, P. Kollar, J. Fuzer, M. Lauda, R. Bureš, and M. Fabérová, “Influence of the resin content on the dynamic energy losses in iron–phenolphormaldehyde resin composites,” IEEE Trans. on Magn. 50 (2014).

Z. Bircáková, P. Kollar, B. Weidenfeller, J. Fuzer, M. Fabérová, and R. Bureš, “Investigation of magnetization processes from the energy losses in soft magnetic composite materials,” Acta Physica Polonica a 131, 684–686 (2017).

L. Ferraris, E. Pošković, F. Franchini, and M. Actis Grande, “Magnetic performance dependence by grain sizes for SMC materials,” EPMA EURO PM2018 Conf. Proc., Bilbao (Spain), 14–18 October 2018.