Effect of granulometry and oxygen content on SMC magnetic properties

EFFECT OF GRANULOMETRY AND OXYGEN CONTENT ON SMC MAGNETIC PROPERTIES

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Abstract
The interest around the adoption of Soft Magnetic Composite materials (SMC) in the realization of electric machines, or parts of electric machines, is continuously increasing. The main reason lies on the opportunity to realize magnetic circuits following a 3D design procedure, which is not allowed with the adoption of the traditional lamination sheets. This is not the only reason, as a lot of research is being carried out on the losses distribution in the magnetic material, particularly as function of the frequency. In this paper different iron powders have been analyzed to investigate the impact of the granulometry on the SMC performance; in particular the grain size and the oxygen content have been considered variable parameters. The materials, prepared, compacted and tested in our laboratories, have been characterized to obtain the magnetic characteristic and information about the iron losses.

Keywords: soft magnetic composites, powder metallurgy, magnetic characterization, iron losses, phenolic resin

1 Introduction
In several widespread applications and plants the energetic aspects have primary importance, therefore research activities are focused to obtain the highest possible efficiencies [1]. In the field of electrical machines various solutions have been proposed with the adoption of new designs of the magnetic circuits, to improve the performance of electromechanical and electromagnetic devices [2], [3]. For this propose, new magnetic materials are being studied in recent years and have been adopted in partial or total substitution of traditional ones [4]-[6].
Dealing with permanent magnets, the use of NdFeB bonded magnets in place of ferrites and, in some occasions, of NdFeB sintered magnets, permits to obtain magnets in complex net shapes with very good magnetic characteristics [7], [8].
Considering the soft magnetic part of electrical machines circuits, laminated steels can be replaced by Soft Magnetic Composites materials commonly known as SMC [9], [10]. In general SMCs are made by very pure iron grains, coated and insulated by a layer, which can be of organic or inorganic typology. Principally such materials allow the freedom to design more

efficient electrical machines, also moving from the traditional two-dimensional stacking constraints characteristic of the classical electrical steels. The use of SMC materials allows the realization of electrical machines with complex geometries obtaining good results for what concerns the reduction of volumes, 3D flux direction, lower eddy currents and lower iron losses at medium and high frequencies [5], [11].
In recent years the development and increase of particular electrical machines owning principally to the adoption of non conventional geometries has been registered, obtaining high efficiency. Some topologies of electrical machines take advantage of SMC materials, such as for example Axial Flux machine (AFM) [12], [13], Transverse Flux machine (TFM) [14], Claw Pole machine (CPM) [15] and other electromechanical devices with particular shapes and applications in medium-high frequencies [16]-[18]. Another positive feature is related to the possibility of using molded parts to assemble electrical machines, thus reducing the production process. In this way, some simplifications in the process activities can be operated with respect to the same machines realized with magnetic sheets.
Several researches have been carried out by the Authors on the aforementioned materials, with promising results both in terms of magnetic and mechanical properties [19]-[21].
The effect of chemistry and processing parameters on the performances of SMC materials have been evaluated in [22]-[24]. However a study of the effect of granulometry and oxygen content onto the characteristics of SMCs does not seem to be present in literature. Therefore in this work the aim is to evaluate, in a preliminary phase, the effect of different granulometries and oxygen contents of powder mixed on the main magnetic characteristics of the materials.
Three iron powders with different grain sizes and different oxygen contents have been evaluated as starting materials for the production of Soft Magnetic Composite.
All powders have been added to 0.2% wt of polymeric phenolic binder to act as insulating layer [21]. The layer is namely covering every single grain and performs the action of electrical insulation and mechanical strength between particles. Phenolic resins are largely used to produce brake pads and can operate at the working temperature of electrical machines and beyond (degrading around 350-400°C). In the research activity three series of SMC samples were produced, comparing different granulometries at the same compacting pressure.

2 Experimental materials and procedures

Several atomized iron powders have been considered with different grain sizes and oxygen contents. The following powders have been chosen: Powder A (average grain value: 45 μm and oxygen content 0.5% in weight), Powder B (average grain value: 150 μm and oxygen content 0.06 wt %) and Powder C (average grain value: 425 μm and oxygen content 0.25 wt %). In this research a phenolic resin, already adopted in previous works [21], [25] has been used. Iron powders have been admixed with 0.2% wt of the resin.
A cylindrical shaped mold, with a diameter of 40 mm has been used to produce the samples, with the compacting pressure fixed at 800MPa. A thermal treatment at 150°C has been carried out and, afterwards, toroidal samples ($\varnothing_{out}$= 40mm $\varnothing_{in}$= 30mm) have been produced to be magnetically tested.
As for comparison, the different iron powders have also been processed without the resin addition. In the case the materials, after compaction at 800MPa, have been sintered in the vacuuming at 1120°C for 1 hour. Samples obtained were undergoing the same characterization as the resin added materials.

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The magnetic characterization was performed at room temperature through a magnetic toroidal test [21], [25], [26]. The measuring system provides a controlled sinusoidal voltage waveform with very low harmonic distortion, without an excessive sample heating – even at high amplitudes – avoiding the need of an additional cooling system. This arrangement is strictly necessary to be able to obtain a correct power measure without the distorted waveforms, which involve a high harmonic content. The whole system (**Fig. 1**) has been designed and prepared in the laboratories of Politecnico di Torino – Alessandria Campus; the automatic acquisition and process elaboration have been developed in LabView environment to obtain the proper magnetic data (**Fig. 2**).

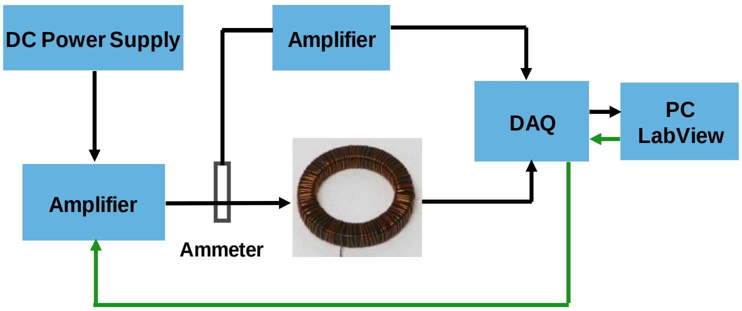

Fig. 1 Scheme of magnetic meusurment and acquisition system

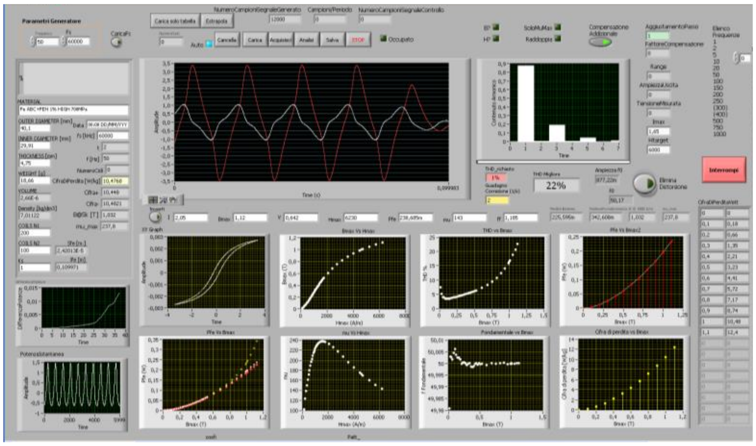

Fig. 2 LabView environment: elaboration process

3 Results

A general feature for magnetic materials is normally provided as the magnetic characteristic B(H); every SMC specimen has been tested as depicted in **Fig. 1**, and the results collected as a function of the granulometry. The obtained magnetic characteristics are shown in **Fig. 3**: the best results in terms of magnetic characteristic are obtained by the intermediate grain sizes SMC B. Big grain sizes magnetic characteristic is slightly lower than intermediate one; on the other hand, the SMC A, made with small particles sizes, doesn't show satisfactory magnetic properties. The high oxygen content for this last composition also leads to a worse magnetic characteristic.

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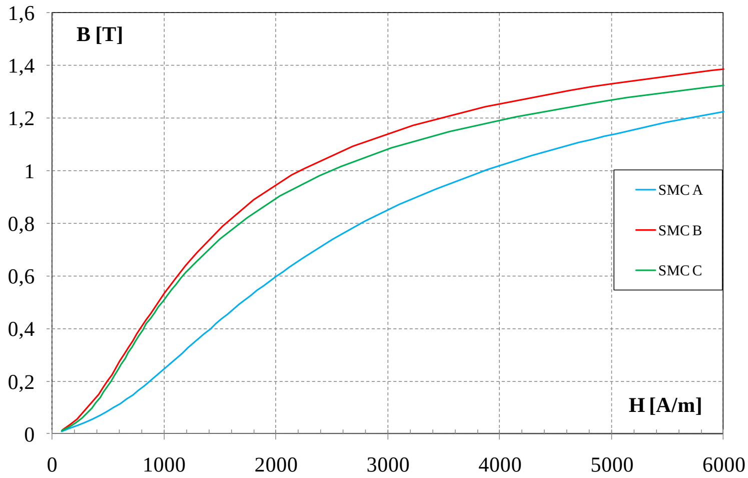

Fig. 3 The magnetic charaterisitcs as fuction of grain sizes

Further data that could be obtained by the magnetic curve B(H) are the maximum magnetic permeability and the magnetic flux density B at 5000 A/m. The results concerning the maximum magnetic permeability are reported in **Fig. 4**: interesting values for SMC B and SMC C are well evident. The same happens for what concerns the magnetic flux density B at 5000 A/m: a satisfactory value is achieved by SMC B as shown in **Fig. 5**. For both magnetic properties, SMC C shows results insufficient for the purpose.

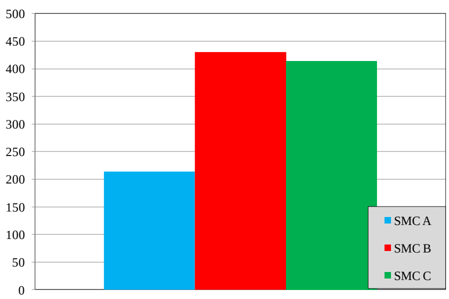

Fig. 4 Maximum magnetic permeability of SMC samples

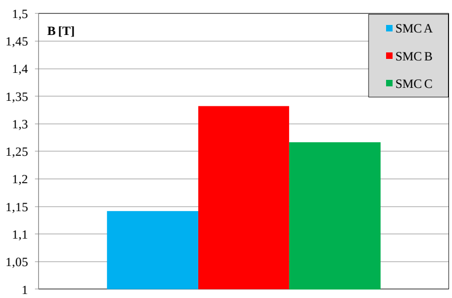

Fig. 5 Magnetic induction B @ 5000 A/m of SMC samples

The specific losses have been measured at 50Hz, 1T, for both the original powder and the proposed SMCs. The original powder specimens, made with sintered process, present the results reported in **Fig. 6**: their iron losses result considerably higher to be used in magnetic circuits subjected to an alternate field.

For what concerns the proposed SMC materials, the specific iron losses have been detected for two different frequencies, 50Hz in **Fig. 7** and 500 Hz in **Fig. 8**, to evaluate their behaviour at two typical frequencies for applications with or without an electronic converters. The SMC B show the best performance for both frequencies; instead for lower frequency SMC C is better than SMC A, while for higher frequency the SMC samples with small granulometry obtain losses

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slightly lower with respect to SMC C. All typologies of SMC samples present losses clearly lower than the original powders (**Fig. 6)**.

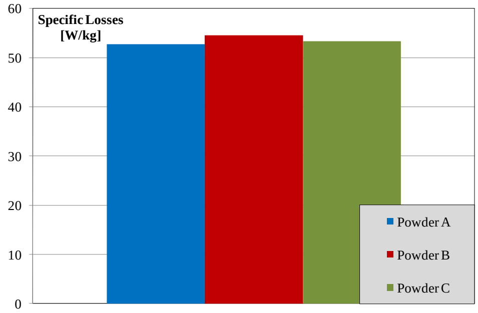

Fig. 6 Specific iron losses for 50Hz @ 1T of original powders

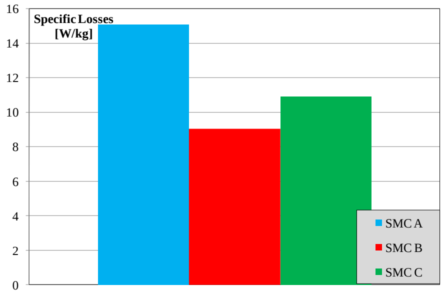

Fig. 7 Specific iron losses for 50Hz @ 1T of SMC samples

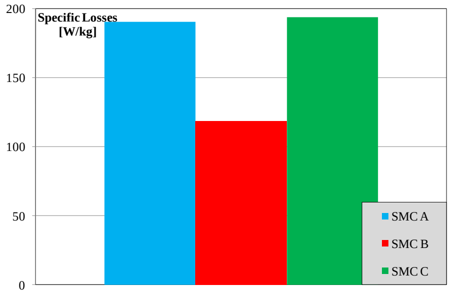

Fig. 8 Specific iron losses for 500Hz @ 1T of SMC samples

The effect of the oxygen content affects a lot the iron losses; for instance, for a ferromagnetic powder very similar to Powder B (same granulometry) but with a lower oxygen content (0.02% in weight) presented in a recent work [25], the iron losses are lower of about 5% with respect to SMC B using the same layer and compacting pressure.

4 Conclusion

The granulometry effect is very strong on the magnetic properties of SMC materials. The intermediate grain sizes show the best magnetic properties for all considered cases. Small particles sizes, SMC A, have in general worse magnetic behaviour. On the other hand big grain sizes, SMC C, are suitable for low frequency applications. In the near future, the particular granulometry compositions will be studied, starting directly from the base powder to obtain the better SMC materials.

The oxygen content seems to affect the iron losses; more focused analysis are however needed to evaluate and understand the mechanisms completely.

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