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Dedicated to the memory of Academician Andrei Ţugulea

FREQUENCY ANALYSIS OF ENERGY LOSSES UNDER SINUSOIDAL MAGNETIC FLUX DENSITY IN COMMERCIAL SOFT MAGNETIC COMPOSITES

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Today soft magnetic composites are innovative materials that could be used in electrical machine production, where new technologies of manufacturing motors with two- or three- dimensional magnetic flux density loci are available. The measurement of the SMC magnetic properties is today considered an important challenge, because high magnetization currents are needed at the saturation point. It is well known that when a small air gap appears in a closed magnetic circuit, the normal magnetization curve has an inclined and more flattened shape. This effect is similar to a shear phenomenon. In powdered SMC materials small air gaps are presented and they are due to the isolation of individual magnetic particles. The high magnetic field strength, which is necessary in the material characterization is directly linked to a high apparent power. A commercial soft magnetic composite was prepared as a toroidal sample with a cross sectional area of 250 mm^2, internal diameter of 61 mm and external diameter equal to 71 mm. It was characterized, using a laboratory digital wattmeter. The normal magnetization curve was determined in quasistatic conditions at the frequency of 3 Hz and the energy losses were measured as a function of the frequency at the peak magnetic polarization J_P of 100 mT, 250 mT and 500 mT. The frequency was variated between 2 Hz and 250 Hz.

1. INTRODUCTION

Today the magnetic materials are very important due to the fact that they are incorporated in many industrial applications. Iron (Fe) is the most used element especially in the composition of different materials as: FeNi, FeNdB, FeSi, or soft ferrites NiZn and MnZn. The amorphous materials and wires, the nanocrystalline structures and soft magnetic composites are the latest development in the soft magnetic materials' production [1–4].

The traditional soft magnetic composite (SMC) consists of iron particles distributed in an organic material matrix. These compounds are today used in electrical machines and they tend to replace the non-oriented silicon strip cores, due to the fact that they have good magnetic permeability, very high saturation magnetic flux density, and high electrical resistivity [2].

Somaloy 500 is a new class of materials that does not contain organic matrix, which leads to some limitations in the manufacturing process. Usually the Fe powder is produced through atomization method, in which molten metal is atomized, by using an inert gas or water under high pressure that conducts to the small metal particles' apparition (Fig. 1). The metallurgical process, which uses water leads to irregular Fe particles (Fig. 2), but if an inert gas is used spherical particles are obtained [3]. The Fe grains are chemically covered with a very thin layer-phosphate glass with a thickness of a few nanometers. The principal preparation method, used for Somaloy 500 is compression moulding, in which a die, filled with magnetic powder (initial compact) is compacted, then the compact material (green compact) is curing in a furnace at the melting point of the binding material (final compact). This production step is made in atmospherically pressure conditions [4].

Apart from high values of magnetic permeability and saturation induction, this material exhibits lower hysteresis losses. Somaloy is considered to be superior to non-oriented alloys, because it has low eddy current losses (classical losses), a 3 dimensional (3D) magnetic flux capability, magnetic and thermal isotropy, high remanent induction, high Curie temperature, and it permits a reduction in weight and size of an electrical machine.

The principal limitation of such a material consists of the fact that the powder metallurgical procedures, used in magnetic core manufacture are not able to produce a wide variety of sizes and shapes of the electrical machine core. Today SMC materials are used in the production of machines that contains a complex 3D flux path such as high speed permanent magnet motors [5], synchronous motors [6], transverse flux machines [7], claw pole permanent magnet motors [8] and axial-flux permanent magnet synchronous machines [9–11]. The soft magnetic composites could be used also in electromagnetic actuators [12, 13] or for electromagnetic shielding [14].

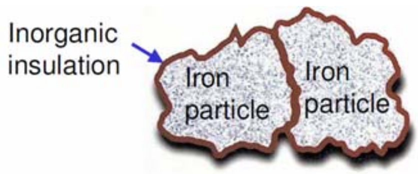

Fig. 1 – Schematic representation of a Fe based SMC [1].

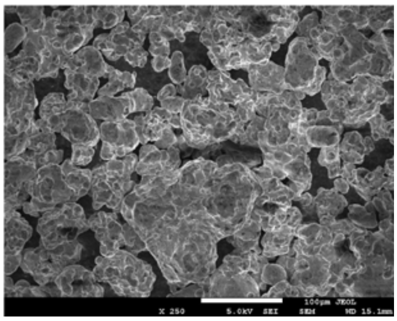

Fig. 2 – Scanning electron microscopy image of Fe particles that have irregular shapes and dimensions [3].

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2. EXPERIMENTAL PROCEDURE

A commercial SMC (Somaloy 500 1 P, Höganäs AB, Sweden) has been analyzed. The additive, used in the sample preparation, is 0.5 % Kenolube [15]. During the compaction phase, the pressure was 800 MPa and the die temperature was 23ºC. The curing temperature was 500ºC and it was made in atmospherically conditions.

The material has the following physical properties: density $\tau = 7370$ kg/m^3, resistivity $\rho = 70$ μΩm, coercive field $H_c = 270$ A/m, maximum relative magnetic permeability $\mu_{max} = 500$, average particle size <*s*> = 280 μm, and a magnetic flux density *B* of 1.51 T, at 10 kA/m. A ring sample with a cross-sectional area of 250 mm^2, an internal diameter of 66 mm and an external diameter equal to 76 mm was prepared for the experimental measurements.

The normal magnetization curve is measured in quasistatic conditions at 3 Hz and the energy loss determination is made under sinusoidal magnetic flux density, starting from 2 Hz up to 250 Hz at the peak magnetic polarization J_p of 100 mT, 250 mT and 500 mT. The magnetizing coil is wound directly on the sample and it has 192 windings, while the coil, used for the magnetic flux measurements contains 20 windings. The primary winding was supplied by a NF HSA4101 power amplifier, driven by an Agilent 33210 arbitrary function generator. For all the measurements the form factor of the secondary voltage was kept in the interval 1.11 ± 0.2 %.

In Fig. 3 is presented the normal magnetization curve, measured at $f = 3$ Hz, by extracting the maximum values of field strength *H* and magnetic polarization *J* from the origin centered symmetrical hysteresis loops. It can be noticed that this composite material has a very high saturation magnetic polarization, higher than 2 T, fact that makes it suitable for high magnetic flux density applications as special electrical machines.

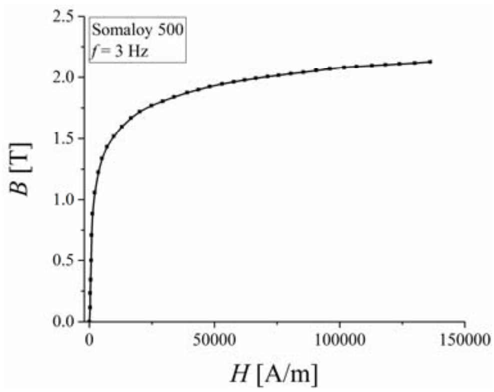

Fig. 3 – Normal magnetization curve of Somaloy 500.

3. PHYSICAL THEORY

The total energy losses in soft magnetic materials, when a sinusoidal magnetization field is applied, can be decomposed in three components: hysteresis W_h, classical W_{cl} and excess W_{exc} energy losses. The hysteresis energy losses can be computed from dc static hysteresis loop area and they are assumed to be frequency independent. The classical energy losses have a linear frequency dependence and they are due to the inhomogeneous material structure and the excess energy losses are determined by the presence of magnetic domains and are generated through the domain wall motion.

3.1. HYSTERESIS ENERGY LOSSES

The hysteresis losses can be experimentally determined through the extrapolation of total energy loss frequency dependence to zero or calculated with an empirical relationship $W_h = K_h J_p^x$, where K_h and x are material parameters, which take into account the structural interaction between the domain walls and the pinning centers that can be observed in the coercive field variation.

3.2. CLASSICAL ENERGY LOSSES

In a SMC there are two different paths for eddy current circulation (Fig. 4). Firstly a path, in which the eddy currents flow between the iron particles in a material with non-insulated particles or in those, whose insulation layer that covers the magnetic particles is damaged by the compaction process ($W_{cl\text{-}1}$). Another path is determined inside the insulated iron particles ($W_{cl\text{-}2}$).

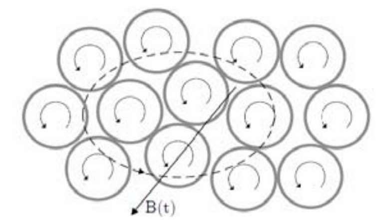

Fig. 4 – Schematic representation of eddy current paths: between and inside each iron particles.

The energy loss analysis carried out in the frequency (*f*) range of 2 Hz up to 250 Hz permits to assess that the classical energy losses, in soft magnetic alloys, can be computed with the following formula:

$$W_{cl} = \frac{\pi^2}{6\rho\tau} J_p^2 t^2 f \;, \tag{1}$$

where: $t = 0.\ 01$ m is the sample thickness. This analytical interpretation is applicable to laminated sheets or samples that have a thickness much lower than the length.

Considering the above mentioned phenomena, regarding the eddy current path, the $W_{cl\text{-}1}$ can be expressed as [16]:

$$W_{cl-1} = \frac{\pi^2}{\beta \rho_{Fe} \tau} J_p^2 t^2 f \;, \tag{2}$$

where ρ_{Fe} is the pure iron resistivity (0.0971 μΩm) and β is a geometrical coefficient, computed as:

$$\beta = \frac{6}{1 - 0.633 \dfrac{w}{t} \tanh\left(1.58 \dfrac{t}{w}\right)} \,, \tag{3}$$

where *w* is the width of the sample (0.025 m).

In the case of a rectangular cross-section of the sample and spherical magnetic particles the $W_{cl\text{-}2}$ can be assumed, considering a sinusoidal magnetic flux density waveform as [17]:

$$W_{cl-2} = \frac{\pi^2}{20\rho_{Fe}\tau} J_p^2 \langle s \rangle^2 f \,. \qquad (4)$$

For more complex geometrical shapes of the magnetic particles and non-rectangular cross-section area the computation of classical energy losses can be achieved through numerical modelling.

To minimize the classical energy losses in a SMC, it can be done by using a reduced size for the magnetic particles, combined with an improved insulation.

3.3. EXCESS ENERGY LOSSES

In the case of excess losses the Bertotti's theory can be applied. According to [18, 19], the magnetization process in the case of a sinusoidal magnetic flux $\varphi(t)$ in a known cross-sectional area S could be described as depending on n simultaneously active regions, which are usually called magnetic objects (MO's).

For Somalloy 500 1P it can be applied the assumption that n is a linear function of two parameters:

$$n = n_0 + H_{exc} / V_0 \,, \qquad (5)$$

where H_{exc} is the excess magnetic field strength that acts on the MO, n_0 is the limit number of the MO's simultaneously active when the measuring frequency f tends to zero at V_0 applied magnetic field strength value.

It can be considered that $H_{exc} = \frac{H_w}{n}$, where H_w = $= 4GSJ_p f/\rho$ is the sum of all magnetic field strengths for the magnetization of one magnetic object, G is a dimensionless coefficient equal to 0.1356 and S is the cross-section of the material.

Using (5) the excess losses relationship is determined as it follows [18, 20, 21]:

$$W_{exc} = 2J_p\left(\sqrt{4V_0 H_w + (n_0 V_0)^2} - n_0 V_0\right). \qquad (6)$$

4. RESULTS AND DISSCUSIONS

The total energy losses versus frequency at the peak magnetic polarization J_p of 100 mT, 250 mT and 500 mT versus frequency are presented in Fig. 5. In the logarithmic scale it could be noticed an almost linear dependence of the energy losses and a direct proportionally increase of the losses with the peak magnetic polarization values.

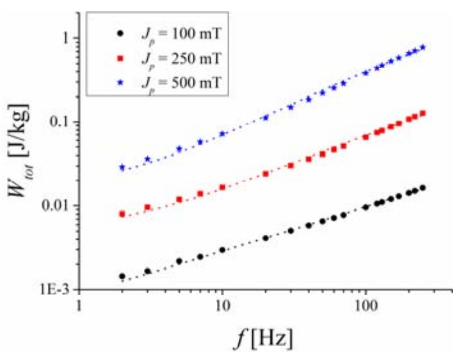

Fig. 5 – Total energy losses versus frequency, in the case of three peak magnetic polarizations J_p (full symbols – experimental values; dotted line – computed values).

The hysteresis losses are independent of the frequency (Fig. 6) and are computed, by extrapolating the total energy losses to the $f = 0$. In SMC the hysteresis energy losses have a lower value, in the case of large particle composite. They can be reduced, by decreasing the number of non-magnetic impurities and by applying an annealing heat treatment after the initial compact phase. Through these procedures the pinning center number could be substantially reduced [1].

The classical energy losses as a function of the frequency are presented in Fig. 7. Firstly, the eddy current losses W_{cl} were computed with (1), by assuming that the entire material is homogenous, because the average magnetic particle size is large. Then, considering the two path for eddy current circulation, the W_{cl-1} and W_{cl-2} components are calculated with (2) and (4). The inter particle losses W_{cl-1} are much lower than the intra particle eddy current losses W_{cl-2}, because in Somaloy 500 1P the iron particle are insulated, and the current paths have a circular shape inside the magnetic particles. The inter particle losses are due to the fact that, during the initial compaction phase the non-magnetic layer is partially destroyed. It can be observed that very small differences appear between the sum of W_{cl-1} and W_{cl-2} and the value of W_{cl}. To reduce the classical energy losses should be used a high quality insulator and the compaction phase has to be done carefully, in order not to destroy the non-magnetic layer.

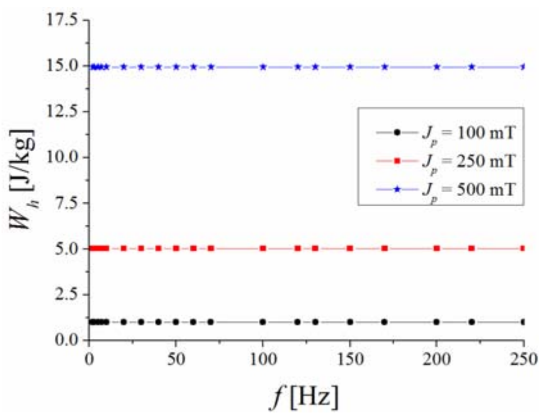

Fig. 6 – Hysteresis energy losses *versus* frequency, in the case of three maximum magnetic polarizations J_p.

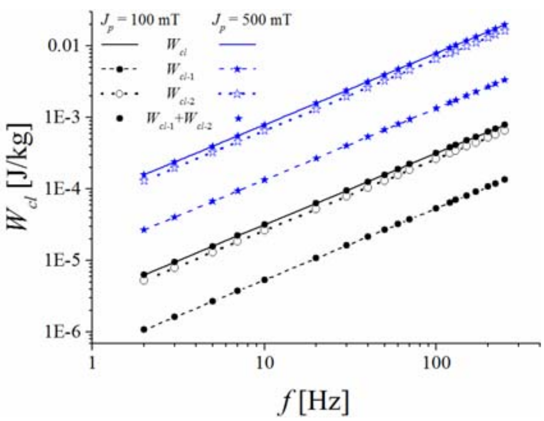

Fig. 7 – Classical energy losses versus frequency, in the case of three maximum magnetic polarizations J_p.

The excess energy losses are important in the Somaloy 500 1P characterization and applications. The two pheno-menological parameters, determined in the case of the three values of the peak magnetic polarizations are presented in Table 1.

Table 1

Values for phenomenological parameters

	J_p = 100 mT	J_p = 250 mT	J_p = 500 mT
n_0	51×10^3	49×10^3	45×10^3
V_0 [A/m]	1.65	8.44	57.61

The number n_0 has higher values than in the case of FeSi laminations [20, 21]. This is due to the fact that few magnetic objects are associated with a magnetic particle, which are dynamically activated by increasing the frequency. It can be concluded that the number of the simultaneously active magnetic objects is the order of 10^3 and it varies in a small amount with the increase of the peak magnetic polarization.

The experimental excess energy loss values were determined by extracting from total energy losses the hysteresis ones and the classical energy losses. Based on (6) the W_{exc} values are computed according the magnetic object theory (Fig. 8).

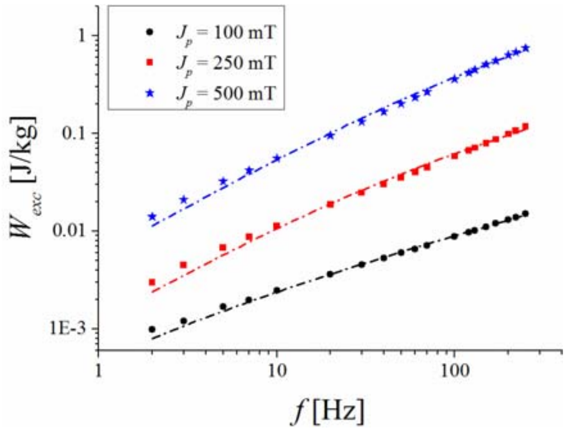

Fig. 8 – Excess energy losses versus frequency, in the case of three maximum magnetic polarizations J_p (full symbols – experimental values; dotted line – computed values).

The computed total energy losses (dotted lines) are compared with the experimental ones (full symbols) and presented in Fig. 5.

5. CONCLUSIONS

The total energy losses in Somaloy 500 1P were measured and analyzed, using the concept of loss separation. The above mentioned conditions, which can be associated with the material structure (number and size of the magnetic particles) permit to determine the classical energy losses within the approximation of bulk magnetic laminations and are closely related to the equations associated with two other paths of eddy current circulation. Regarding the excess loss component the statistical theory of losses, based on magnetic objects, can describe correctly the frequency dependence of the losses.

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